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ABSTRACT

Various published computer programs for fixed/broadcast communication satellite system synthesis and optimization are discussed. The rationale for selecting General Dynamics/Convair's Satellite Telecommunication Analysis and Modeling Program (STAMP) in modified form to aid in the system costing and sensitivity analysis work in the Program on Application of Communication Satellites to Educational Development is given. Modifications of STAMP implemented on Washington University's IBM 360/65 computer include: 1) extension of the six beam capability to eight; 2) an option for generation of multiple beams from a single reflector system with an array of feeds; 3) improved system costing to reflect the time-value of money, growth in earth-terminal population with time, and to account for measures of system reliability; 4) inclusion of model for scintillation at microwave frequencies in the communication link loss model; and 5) an updated technological environment. Results of a sensitivity analysis of the modified STAMP are discussed to indicate the program's capabilities. Also described are computer programs for plotting footprints of narrowbeam antennae onboard on earth-synchronous satellite, full field of view for a prescribed subsatellite point, and contours of earth station antennae elevation angles. (Author)

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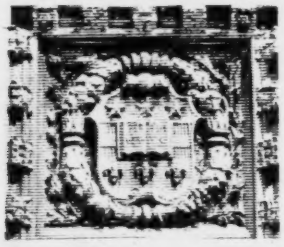

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COMPUTER-AIDED COMMUNICATION SATELLITE SYSTEM

ANALYSIS AND OPTIMIZATION

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PROGRAM ON APPLICATION OF COMMUNICATIONS SATELLITES
TO EDUCATIONAL DEVELOPMENT

Center for Development Technology
(Communications Group)

Washington University

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U.S. DEPARTMENT OF HEALTH, EDUCATION & WELFARE
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COMPUTER-AIDED COMMUNICATION SATELLITE SYSTEM ANALYSIS AND OPTIMIZATION

Abstract

The capabilities and limitations of the various published computer programs for fixed/broadcast communication satellite system synthesis and optimization are discussed. The rationale for the selection of General Dynamics/Convair's Satellite Telecommunication Analysis and Modeling Program (STAMP) in an extensively modified form to aid in the system costing and sensitivity analysis work in the Program on Application of Communication Satellites to Educational Development is given. The modifications made to STAMP implemented on Washington University's IBM 360/65 computer system include: extension of the six beam capability to eight; addition of an option for generation of multiple beams from a single reflector system with an array of feeds; an improved system costing to reflect the time-value of money, growth in earth-terminal population with time, and to account for various measures of system reliability; inclusion of a model for scintillation at microwave frequencies in the communication link loss model; and, an updated technological environment. The results of a preliminary sensitivity analysis carried out with the modified STAMP are discussed to illuminate the capabilities of the modified program. Also described are computer programs developed for plotting footprints of narrowbeam antennae onboard an earth-synchronous satellite, full field of view for a prescribed subsatellite point, and contours of earth-station antenna elevation angles.

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COMPUTER-AIDED COMMUNICATION SATELLITE SYSTEM ANALYSIS AND OPTIMIZATION

1. INTRODUCTION

1.1 BACKGROUND

The Center for Development Technology at the Washington University has undertaken a research effort in the area of the application of fixed/broadcast communication satellites to U.S. education for delivery of various educational services and information networking. The objectives of the study, sponsored by the National Aeronautics and Space Administration (NASA), are to identify opportunities for utilizing fixed/broadcast satellite services in U.S. education, to study the economics and feasibility of the various satellite applications in the education sector, and to devise systems and strategies for utilizing communication satellites for improvement of U.S. education.(1)* Design of minimum cost fixed/broadcast satellite systems for a given set of user and technical requirements and environment is thus, obviously a matter of concern to the research

*The numbers in parentheses in the text indicate references in the Bibliography.

effort and so is the analysis of system design and cost sensitivities to factors such as traffic load, system performance and reliability requirements, coverage objectives, services, operational frequencies, earth-terminal variety, population and growth-rate, satellite life-time, launch vehicle choices, and various probabilities of successful orbital placement of the satellite for the purpose of identifying critical user requirements, system parameters, and technology.

Earth and space segment trade-offs in a communication satellite system have been a subject of interest to many individuals and organizations.(2-8) The technique almost universally adopted in these studies has been the establishment of quantitative relationships, first among the various earth and space segment parameters separately and then among those relating the two segments, followed by the analysis of the impact of certain parameters assuming certain values on the overall system or a segment thereof. Unfortunately, most of the studies are either limited to earth segment optimization for fixed space segment parameters, (2) or determination of satellite parameters which maximize voice channel capacity of a link between two standard INTELSAT earth-stations,(3,4) or modeling of space segment alone.(5)

Lutz first presented the complex relationship between the earth-station parameters (antenna gain, system noise temperature, and transmitter power), the space segment

charges of the satellite, and performance characteristics of the satellite transponder.(2) However, Lutz did not establish a comprehensive space segment model and excluded considerations such as channel capacity, signal-quality, coverage requirements and earth-terminal population growth characteristics from his optimization. As a result, his "optimal systems or configurations" were generally sub-optimal in nature. Hasselbacher was first to attempt modeling space-segment (satellite configurations and sub-systems) in detail along with the earth-segment but fell short of giving a methodology for the determination of lowest-cost system for a given set of user requirements.(6) Bergin et al.'s Satellite Telecommunication Analysis and Modeling Program (STAMP), developed for NASA under Information Transfer Satellite Concept Study program, represents the first effort, described in open literature, which utilizes a total system approach and employs a steepest descent algorithm to determine the minimum cost system configuration subject to the fixed user requirements and imposed constraints.(7) The ground and space segment are simultaneously synthesized and in the process of converging to the solution, the pertinent sub-system trade-offs are resolved. Since the publication of Bergin et al.'s work in 1971, two other studies in this area have been reported. Knouse et al. have developed a computer program for NASA for determining minimum cost broadcast satellite systems for fixed user requirements (8) while Potter has written a

computer program for defining optimum satellite teleconferencing networks for a given set of user requirements.(9) Whereas Knouse et al. model and synthesize earth and space segments simultaneously along the lines of Bergin et al., Potter determines optimum or lowest-cost earth segment with respect to space segment modelled only in terms of the annual cost of 1 watt of satellite RF power.

The user requirement investigations conducted at Washington University suggest that educational satellite service requirements are neither going to be solely broadcast type nor totally fixed or point-to-point or those that fall under the teleconferencing services described by Potter.(1,9) The educational requirements for satellite services in the U.S. represent a mixture of the above-mentioned three categories. Selection of an appropriate tool for the analysis of the system cost and sensitivity thus posed a serious problem. While Knouse et al.'s computer program was most up to date in terms of the state-of-the-art reflected in various parametric equations or models, it could only handle broadcast systems whereas Bergin et al.'s models had become slightly out-of-date and questionable though conceptually capable of handling our analysis requirements to a large extent. For these reasons we decided to adapt Bergin et al.'s STAMP computer program to our needs. This report describes the modified STAMP program which has been developed to aid in our system definition and cost analysis efforts. The major modifications in the program

include updating of the state-of-the-art of the ground as well as space segment technology, extension of the six beam capability to eight beams, inclusion of a scintillation loss model in the up- and down-link models, and improvements in the economic basis for system cost determination. To facilitate comparison of systems with different satellite and system lifetimes and earth-station population growth models, computation of the system cost has been modified to reflect present value of future investments. Also described are the results of some of the preliminary work carried out with the help of the modified STAMP to compare design alternatives and to determine sensitivities to various system parameters.

1.2 SCOPE OF WORK

Sections 1.3-1.5 of this chapter briefly introduce and discuss the main features of the computer programs developed by Knouse et al.,(8) Potter (9) and Bergin et al. (7) for NASA. This discussion is followed by a comparison of the three programs in terms of their capabilities and limitations.

Chapter 2 describes Bergin et al.'s original STAMP(7) in detail, the various sub-system models, the optimization technique, the input and output formats and features, the architecture of the program and its implementation on Washington University's IBM 360/65 computer.

Chapter 3 discusses the various modifications made in the STAMP program to reflect the technological developments that have come into light since 1970, when the work on STAMP was completed by Bergin et al. at the Convair Division of the General Dynamics Corporation. Included are:

- The extension of the six beam capability to eight;
- Addition of the option for a multibeam spacecraft antenna;
- Substitution of cost-performance relationships for low-cost ground receivers with wideband front-ends capable of handling multiple carriers with a small additional cost for processing each additional carrier for a situation where each carrier required a separate receiver;
- Provision of system costing on the basis of present value to provide an improved basis for comparison of alternative systems and handling of different earth-terminal population growth characteristics and system reliability considerations;
- Incorporation of an ionospheric scintillation loss model for microwave frequencies, derived from Communications Satellite Corporation (COMSAT) measurements,(10) to the up- and down-link models;
- Removal of all amplitude modulation options from STAMP: and
- Inclusion of appropriate changes in the output format.

Chapter 4 of this report describes some sample runs made with the modified STAMP along with an analysis of the impact of certain user and technological requirements on system design and cost. Chapter 5 summarizes the results along with suggestions for future work.

A group of computer programs have been written to plot the footprints of narrowbeam satellite antennae on a computer generated geographical map for a given sub-satellite point, beam dimensions and beam centers; perspective from a given geostationary orbit location and contours of earth-station antenna elevation angles for values specified. These programs, developed to aid in the system specification and analysis, are discussed in Appendix 7.1. Appendix 7.2 contains a listing of the modified STAMP program.

1.3 STANFORD UNIVERSITY PROGRAM (9)

The work at the Institute for Public Policy Analysis at Stanford University has been primarily concerned with communication satellite systems for teleconferencing purposes.(9) In general, the system is composed of a single master ground station that transmits a number of wideband video channels and N slave ground stations that each receive the wideband signal and return a single narrowband audio or digital channel. The satellite has a wideband video transponder and a narrowband return transponder. It has a single antenna with a single beam covering the master station and all N slave stations.

The first step in the optimization procedure is to obtain the costing parameters for the ground system. The receiver is considered first and is described in terms of the antenna gain (G) and the receiving system noise temperature (T) by the figure of merit G/T, dB/°K. To obtain the minimum cost combination of antenna size and pre-amplifier noise-performance for any given value of G/T, a curve of antenna diameter versus G/T for a number of system noise temperatures is obtained. A value for G/T is then selected and for each constant temperature line, that contains that value of G/T, a value for the antenna diameter and the receiver noise temperature is specified.

A cost is then obtained for an antenna of the specified diameter (D) and front-end for the specified noise temperature (T,°K) from historical cost data and vender quotes. This cost is determined for all possible values of D and T for the chosen value of G/T. A new value of G/T is then chosen and the process is repeated. The minimum cost for each value of G/T is then plotted on a graph of antenna diameter versus G/T. This, then, is a graph of the combinations of antenna diameter and pre-amplifier that will yield a least cost receiver system for any given G/T. The transmitter cost is given as a function of the output power.

The next step is to obtain the space segment costs. This is done by considering three candidate satellites, one small, one medium and one large. The satellite that provides the most RF power per dollar per year for a particular demand

function is assumed optimum for that demand function. There are three types of demand functions considered in the report; they are 1) a constant demand, 2) linear growth for a specified span, constant demand thereafter, and 3) linear demand growth forever. Associated with each of these demand functions is a number of launch streams that will satisfy the demand. For each of these launch streams the costs are computed in two ways, one with an in-orbit spare and one with a ground spare. An equation is then developed which gives the present value of the total investment for the space segment based on the development and recurring costs of each of the candidate satellites and launch vehicles, the failure rates for satellites and launch vehicles, the discount rate and the particular launch stream chosen. The figure of merit of the space segment, the annual cost per watt of RF power, is then computed such that the present value of the annual income over entire system lifetime will equal the present value of the investment. This has been done for each of the demand functions for various interest rates. A number of conclusions are drawn to aid in the choice of one of the three candidate satellites and an appropriate launch stream to satisfy a particular demand function.

With this analysis in mind one is in a position to determine the optimum, or minimum cost, system. Several parameters must be known prior to the determination of the

optimum system, these are the uplink and downlink frequencies of the narrowband and wideband signals, the desired area of coverage, which determine the satellite antenna diameter, the satellite transponder noise temperature, cost data for various system elements, and the annual cost per RF watt of the satellite transponder.

The total noise in the system is constrained by the required signal-to-noise ratio (SNR) and is described by the carrier to noise ratio (C/T). The total noise (T_{total}) is contributed by uplink noise (T_u), intermodulation noise (T_{im}) and downlink noise (T_d), such that:

$$(T/C)_t = (T/C)_u + (T/C)_{im} + (T/C)_d$$

Now if $C/T_u = X \cdot C/T_d$ then the total noise contributed by the uplink and downlink is divided between the two. The total system cost is very much dependent on the value chosen for X. The backoff of the satellite transponder is also taken into account. Given a value of X, which divides the noise for the video segment, Y, which divides the noise for the audio segment and a backoff value (BO) for the transponder handling narrowband return-links, the analysis of the master and slave stations is decoupled and carried out independent of each other.

The procedure used in the Stanford University study to obtain the minimum cost system is shown in Figure 1. First the number of TV channels is chosen, then the number of slave stations is specified followed by specification of

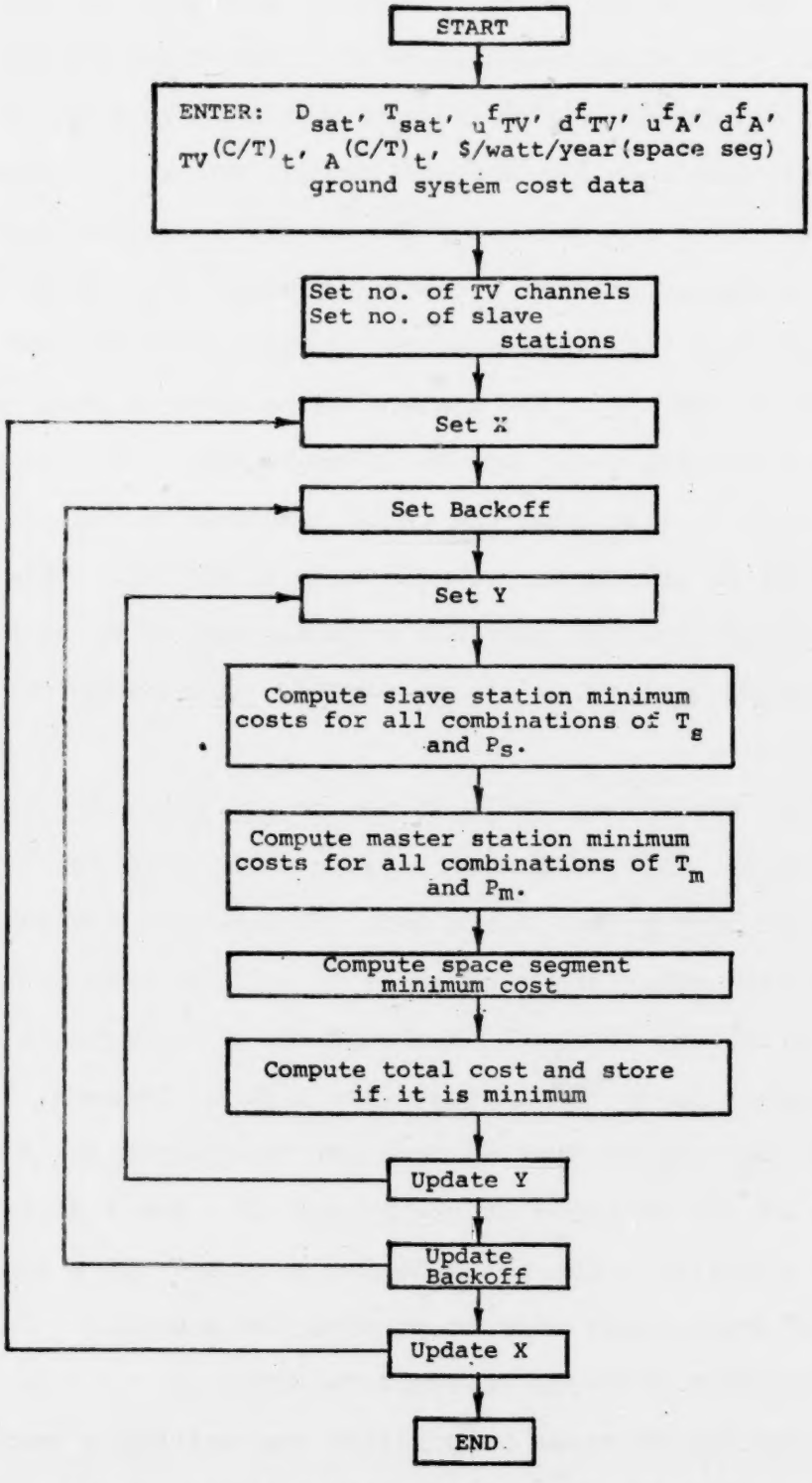

START
ENTER: D_{sat}, T_{sat}, u^f_{TV}, d^f_{TV}, u^f_A, d^f_A, $_{TV}(C/T)_t$, $_A(C/T)_t$, $/watt/year(space seg) ground system cost data
Set no. of TV channels
Set no. of slave stations
Set X
Set Backoff
Set Y
Compute slave station minimum costs for all combinations of T_s and P_s.
Compute master station minimum costs for all combinations of T_m and P_m.
Compute space segment minimum cost
Compute total cost and store if it is minimum
Update Y
Update Backoff
Update X
END

Figure 1: Algorithm Used in Stanford Program (9)

values for X, BO and Y. A search is made over all values of slave station noise temperature (T_s) and slave station transmitter power (P_s) to be considered to find the minimum slave station cost for the triplet (X, BO, Y). A search is then made over all values of master station noise temperature (T_m) and master station transmitter power (P_m) to be considered to find the minimum master station cost for the given triplet (X, BO, Y). The minimum space segment cost is then computed and the total system is evaluated. If this value of total cost is less than the value computed on the previous iteration it is stored, if not it is discarded. This process is continued for all possible combinations of X, BO and Y. When all possibilities are exhausted, the minimum cost will be available.

This algorithm, while it may be practical for some application, is rather inefficient. There should be some method of convergence built into the iteration scheme rather than calculating the cost of all possible systems and picking the minimum. Although the main emphasis of this report is on the master-slave type of network, the methodology can be applied to other configurations as it is in one of the sections of the report.(9) The algorithm itself simplifies the optimization but requires a good deal of preliminary work to provide the inputs.

1.4 COMPUTER SCIENCES CORPORATION STUDY (8)

Computer Sciences Corporation has written a computer program for synthesizing broadcast satellite systems. The

system is composed of one or more satellites broadcasting FM video signals accompanied by one or more audio signals, and a ground segment consisting of a large number of receivers of the same kind.

The computer program model does not include the uplink transmitting facilities and the tracking, telemetry and command facilities.

The inputs to the program include 1) A system description in terms of the number of antenna beams (1-6), subsatellite point, number of video channels/beam, number of audio channels/video channel, etc.; 2) Carrier frequencies for each of the video channels; 3) Receiver description in terms of required video and audio SNR's, maximum RF bandwidth, FM threshold, video and audio guard bandwidths, peak deviation of subcarriers, etc.; 4) Beam description for each beam in terms of beam center location, beamwidth, satellite and ground antenna efficiencies, number of receivers, maximum allowable video and audio bandwidth and various parameters describing losses and noises and receiver cost.

The first step in the synthesis of lowest-cost system is the computation of the maximum value for G/T of the ground receiver for the input values of minimum beamwidth and the minimum receiver noise temperature available.

An initial value for G/T, system noise temperature, equivalent isotropic radiated power (EIRP) per channel and RF power per channel is computed. If the present value of

G/T is greater than the maximum value of G/T computed earlier, then EIRP/channel and RF/channel are increased by a given amount and G/T is decreased by some other factor until a suitable value is obtained.

There are four types of receivers considered that differ in the type of front end used. The four types of receiver front ends are: 1) a mixer, 2) a transistor amplifier, 3) a tunnel diode amplifier, and 4) a parametric amplifier.

The costs of a single receiver is calculated for each of four receiver types. The antenna diameters are calculated to provide the present value of G/T for each receiver type, and the corresponding antenna costs are calculated. If any antenna diameter exceeds the maximum allowable, its cost is set at an arbitrarily high value to effectively eliminate it from consideration. The minimum cost combination of receiver and antenna is chosen and multiplied by the number of ground receivers to obtain the total ground segment cost.

The satellite size, weight and power parameters are calculated, a launch vehicle is chosen and the total space segment cost is computed. The RF power/channel and EIRP/channel are then halved, the value for G/T is increased by 3 dB and the procedure is repeated. This continues until the G/T exceeds the maximum G/T or the total system cost increases. At this point the variables RF power/channel, EIRP/channel and G/T are modified to provide a number of

additional iteration points to more precisely define the minimum cost system.

Figure 2 is a graphical display of a sample run of the CSC program. The minimum cost is shown to be rather flat so that increasing or decreasing the EIRP/channel does not effect the system cost greatly while it does noticeably effect the ground and space segment costs. This flatness is dependent on system parameters and may not always be present. In some system trade-offs, a local minimum may be present. The CSC program seems to be susceptible to these local minima. To remedy this problem, if one runs the program and suspects that the obtained minimum cost system is actually a local minimum he can rerun the program with the same input parameters with the exception of the initial value of EIRP/channel. This should be a value lower than the value defined to be optimum by the first run of the program. The results of the second run could be compared to those of the first to determine if the local minimum actually existed.

1.5 GENERAL DYNAMICS/CONVAIR STUDY (7)

Convair Aerospace Division of General Dynamics Corporation conducted a study which had as one if its main objectives to develop techniques for planning communication satellite systems. One of the products of this study was a computer program for obtaining a minimum cost system and for analyzing system sensitivity to various parameters for broadcast as well as fixed communication satellite systems.

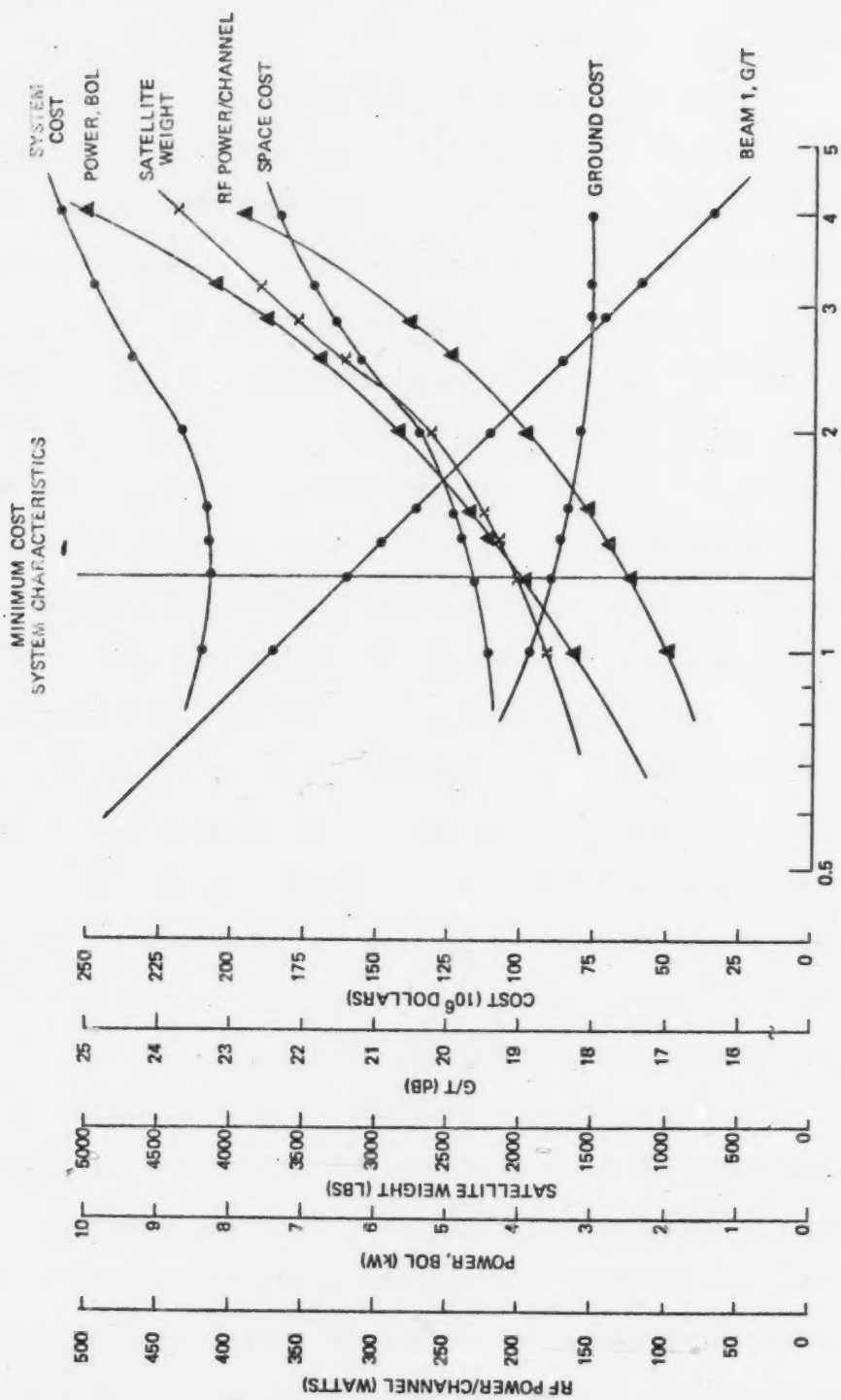


Figure 2: Graphical Display of a Typical CSC Run for a Satellite System With 6 Video Channel/Beam, 49 dB S_{B-W}/N_{rms} (8)

The program accepts as input a set of user requirements and the parametric data that determine weight, volume, cost and performance of the various subsystems. The channel requirements, i.e. carrier to noise ratio, bandwidths, and the number of channels, carriers and transmitters per beam, are computed based on the user requirements. The satellite antenna is sized based on the operating frequency and the desired beamwidths. Then the loss and noise terms are computed and the satellite subsystem types are defined. The vector of independent parameters, the X vector, is initialized to the initial values that were input and the dependent parameter vector, the Y vector, is computed. An optimum perturbation of the X vector is determined and the perturbed X is used to calculate a new Y vector. This continues until convergence is achieved or until the maximum specified number of iterations is reached.

This program is one of the most comprehensive of its kind. In any single run three different classes of ground facilities may be defined with different signal quality, channel capacity and transmit/receive capability. The satellite may have one to six antenna beams with a separate antenna for each beam. The total system is synthesized by the program including the satellite(s), launch vehicle and ground facilities. All these systems are included in the optimization procedure such that changing a parameter in any system will be reflected in the other systems. A

modular approach was utilized in the structure of the program with a separate subroutine for each of the subsystems.

The main advantage of this program is the fact that after each iteration an optimum perturbation of the independent parameters is computed. These perturbations are always in the direction of minimum cost. Also the step size for each of the parameters is adjusted such that when the present iteration is far from the optimum the step size is larger than when it is close to convergence. This feature helps to avoid local minima far from the optimum point by "stepping over them" with a large step size.

1.6 COMPARISON OF GD/C, CSC AND STANFORD UNIVERSITY COMPUTER PROGRAMS

A comparison of the three system synthesis programs indicates that the Stanford program is the least efficient of the three since its technique is to check all possible combinations of independent variables and choose the one that defines the least cost system. It does have an advantage over the CSC program in the fact that it accounts for the annual system operating costs in its total system cost. However, it requires, as part of its input, the annual cost per watt of the satellite. Although the Stanford report contains a lengthy discussion of the determination of the minimum cost per watt per year as a function of the interest rate, it is, nevertheless, a cumbersome manual derivation.

The CSC program does have an optimization technique but it, along with the Stanford program, is limited to broadcast

satellite systems. Although the Stanford program includes the uplink in its system, the CSC program assumes that this portion of the system cost does not effect the system optimization and is left out.

The GD/C program, on the other hand, is capable of handling numerous configurations of both fixed and broadcast satellite systems. It includes the annual costs of the system but does not take into account the effect of interest over the, generally, long system lifetimes. It has the most sophisticated optimization technique of the three programs and the most complete system definition contained in the output.

2. DESCRIPTION OF THE GD/C PROGRAM

2.1 PURPOSE AND SCOPE

The General Dynamics Satellite System Synthesis Program, (7) called STAMP (Satellite Telecommunication Analysis and Modeling Program), was written as a tool for analyzing satellite communication system requirements. The program synthesizes a least cost satellite communication system within the constraints of satellite size, power levels, antenna diameters and receiver noise figures while satisfying the user requirements of area of coverage and type and grade of service.

The program incorporates the total system in its optimization. This includes up to three separate types of ground facilities, one or more identical satellites, launch vehicles and uplink and downlink propagation models.

Communication can be handled in any one or combination of four data types: audio, video, facsimile and digital. Each beam is considered separately by the program. This eliminates the need to choose a worst case beam and assume all other beams are identical. Each individual beam can handle any combination of the four data types. A block diagram of the program is shown in Figure 3.

The input to the program is read in through the namelist feature. There are seven namelist lists each containing parameters that are related to a specific area of the program. The lists are:

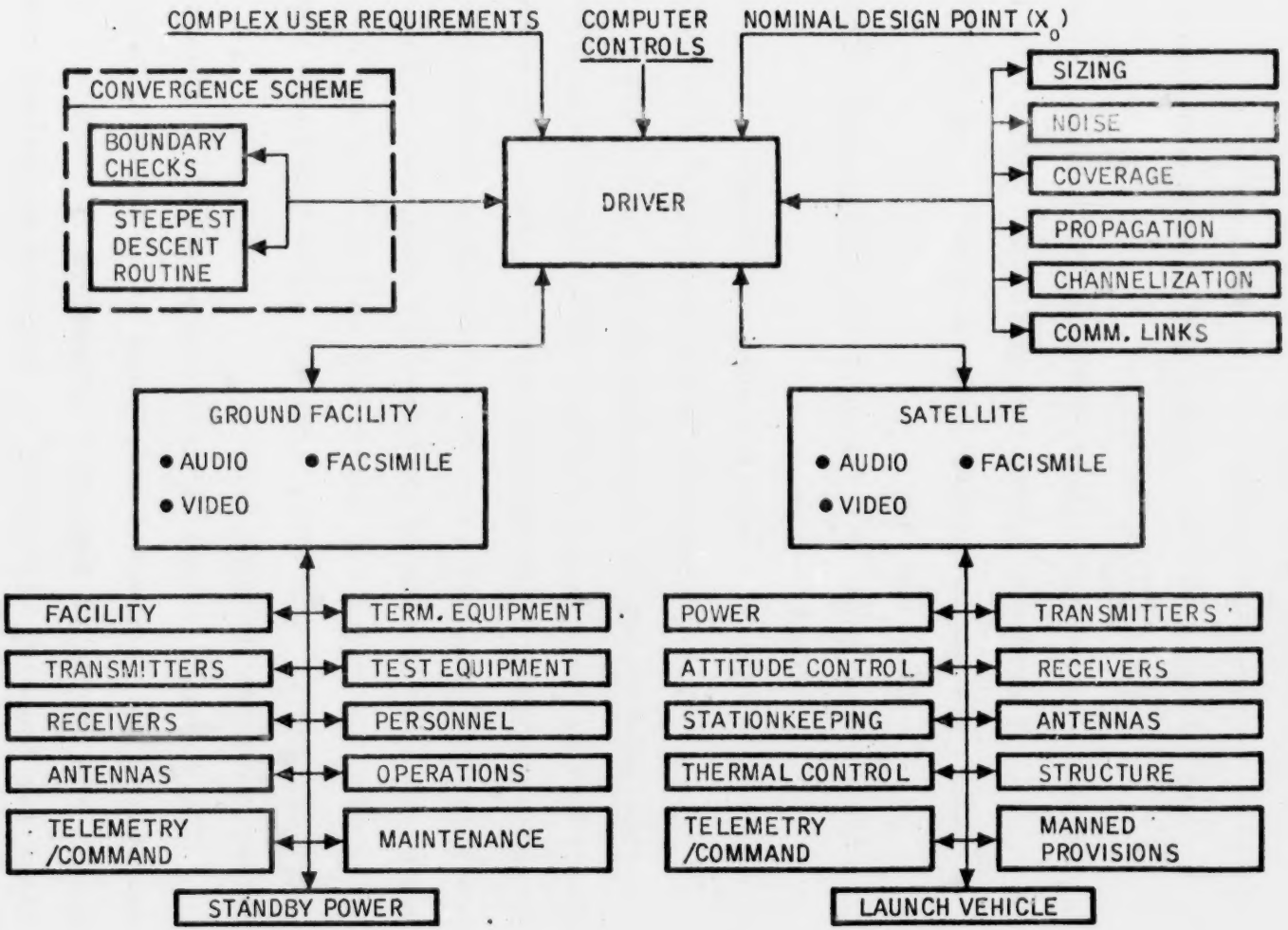


Figure 3: STAMP Block Diagram (7)

SATT - contains coefficients for satellite weight, volume, cost and power equations

PAR - contains general system parameters

LOSS - contains coefficient for determining signal attenuation and noise

REDUND - contains parameters needed to reflect redundant elements needed for additional spacecraft life

GRD12 - contains coefficient for class 1 and 2 ground facility cost

GRD3 - contains coefficients for direct class ground facility cost

USRQ - contains specific user requirements and program control parameters for each case to be run.

The program begins by reading in the input data. It then computes the channel characteristics including carrier to noise ratios and transponder backoff terms. The spacecraft antenna is sized based on the required frequencies and beamwidth and the area of coverage for each beam is computed along with the elevation angles and uplink and downlink location losses. The other loss and noise terms are then determined from the link model.

The boundary values for the dependent and independent parameters are determined and, based on an initial design point, the vector of dependent parameters is computed. A check for boundary violations is made and an optimal perturbation of the independent parameters is determined. If convergence has not been attained the perturbed independent

parameters are used to compute a new dependent parameter vector. This repeats until convergence is achieved at which time the formalized output is printed and a check is made to determine whether another case is to be run. The flow diagram of the program is shown in Figure 4.

The program can be used for determining sensitivity of the system cost to various parameters such as system capacity, coverage, signal to noise ratios, transmitter types, receiver noise environment, satellite lifetimes, etc.

2.2 SUBSYSTEM MODELS

The program is broken into individual subsystem models, each represented by a separate subroutine. This simplifies changes in any particular subsystem model. The volume, weight and cost data are obtained from curves derived from historical data and vendor quotes. The coefficients defining these curves are included in the input data. This allows the program to be easily updated to current technology without a major programming change.

2.2.1 Uplink and Downlink Models

The communication links are covered in three separate models: a) communication model, b) antenna coverage model, and c) noise and propagation models.

2.2.1.1 Communication Model

This model contains equations for modeling the transmission, reception and propagation medium. A diagram of the model is shown in Figure 5. The subroutine that deals with this model is CHANEL. The main outputs of this subroutine

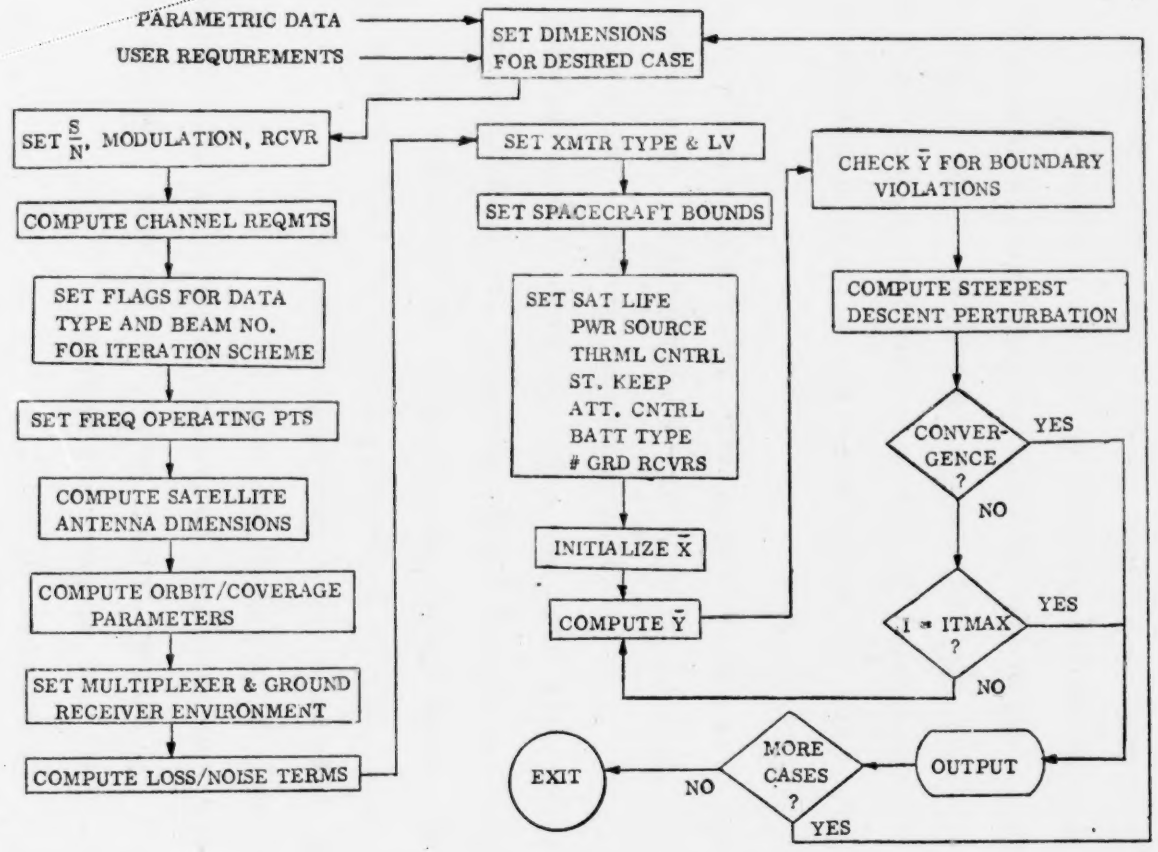
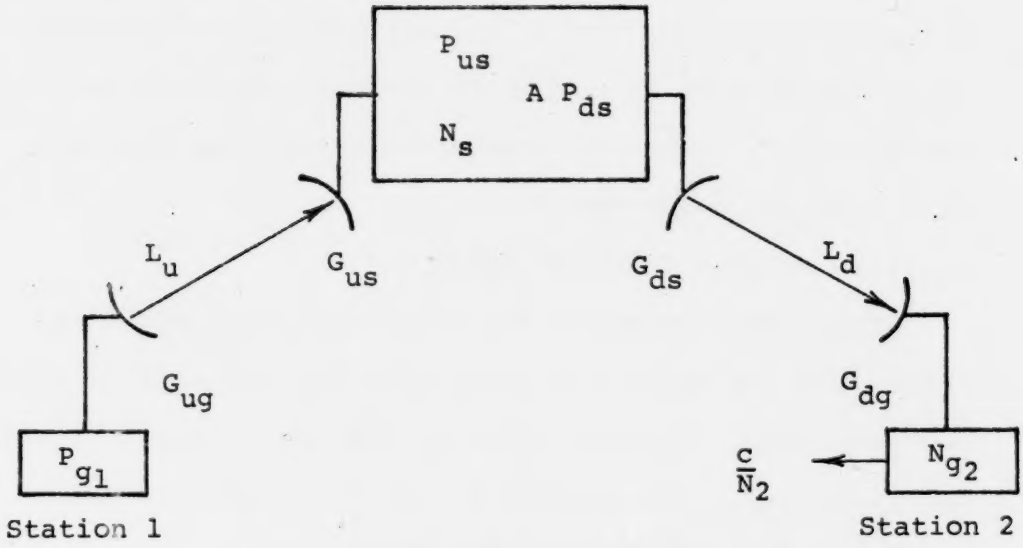


Figure 4: Flow Diagram of STAMP



Where G = antenna gain
P = transmitter power
L = system attenuation
N = system noise power
A = satellite transponder gain

Subscripts:

u = uplink
d = downlink
g = ground station
s = satellite
1 = ground station 1
2 = ground station 2

Figure 5: Communication Model

are the necessary RF bandwidths for the various data types and the carrier to noise ratio for each data type and class of ground facility. Other outputs are various channel requirements such as number of carriers per beam on uplink and downlink, number of transmitters per beam for each data type and beam, etc.

2.2.1.2 Antenna Coverage Model

This model computes the elevation angle and slant ranges and the major and minor axes for the area of coverage for each beam. It then computes the losses due to location for each beam. The subroutine for this model is AOC.

2.2.1.3 Noise and Propagation Model

This model accepts as input the elevation angles and slant ranges from subroutine AOC and computes the attenuation due to the sky, man-made and earth elements. The elements in the model include ionosphere, clouds, rain, water vapor, oxygen, and receiver circuit losses. A diagram of the model is shown in Figure 6. The noise elements are expressed as an equivalent noise temperature. The effective noise at the ground receiving station is:

$$T_g = L_{tl}\, T_{ant} + T_t + T_{rcvr}$$

where T_{rcvr} = noise temperature of the receiver; T_t = noise temperature of transmission line; $L_{tl}\, T_{ant}$ represents all external noise entering the system by way of the antenna attenuated by the transmission line loss. The field of this antenna is divided into three regions; sky, horizontal and earth, to discriminate noise sources in sky, man-made

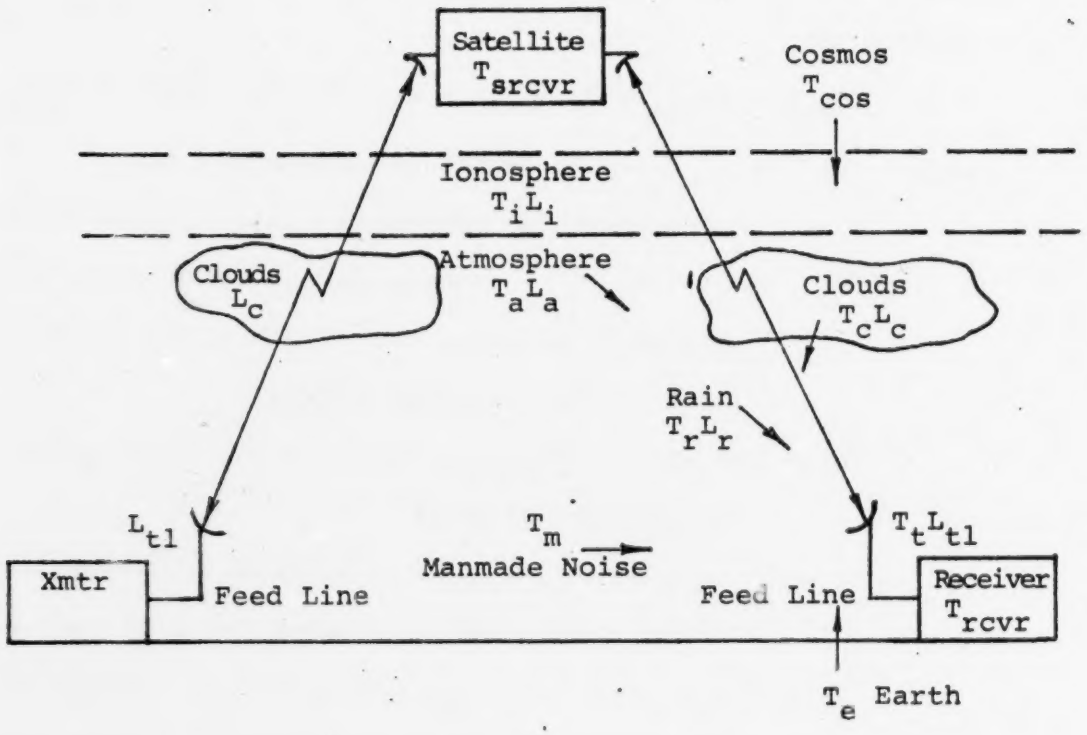


Figure 6: Noise and Propagation Models

noise sources and the earth as a noise source. These noise sources are amplified by the respective relative gain over each region, G_s, G_m, and G_e. The gains are expressed as the integral of the antenna pattern function normalized in steradians. The noise temperature of the antenna is then written as:

$$T_{ant} = (T_{cos} + T_i + T_a + T_c + T_r)G_s + T_m G_m + T_e G_e$$

where $T_e = L_{rh} T_{man}$; man-made environmental noise attenuated by horizontal path through rain.

$T_r = (1 - L_r) T_{rain}$; noise due to rain minus noise absorbed by rain, i.e. fraction of noise due to rain that reaches receiver.

$T_c = L_r (1 - L_c) T_{cloud}$; fraction of cloud noise attenuated by rain.

$T_a = L_e L_r (1 - L_a) T_{atm}$; fraction of atmospheric noise attenuated by clouds and rain.

$T_i = L_a L_e L_r (1 - L_i) T_{ion}$; fraction of ionospheric noise attenuated by atmosphere, clouds and rain.

$T_{cos} = L_i L_a L_e L_r T_{cosmic}$; cosmic noise attenuated by ionosphere, atmosphere, clouds and rain.

In all these equations, the attenuation term, L, is the reciprocal of the loss such that the value lies between 0 and 1.

2.2.2 Ground Stations

The ground system model includes transmitters, receivers and antennas as well as terminal equipment, buildings, standby power, test equipment, personnel, installation and checkout.

There are three types of ground stations designated Class 1, Class 2 and direct stations. The Class 1 and Class 2 station models include transmitting and receiving facilities as well as the building, personnel and associated equipment. The direct station consists only of antenna and receiver/preamplifier. These are intended to be low-cost, mass produced, in-home broadcast receivers.

There are nine different ground system options shown in Table 1.

2.2.2.1 Cost Models

The costing for the ground system is divided into four categories, the unit recurring cost, the installation cost, the operations cost and the maintenance cost. The unit recurring and installation cost are one time costs while the operation and maintenance costs are calculated on a per year basis and summed over the lifetime of the system without regard for the time-value of money.

Table 2 shows the costs associated with each of the elements of the ground system.

The costs quoted in the following paragraphs were determined from studies performed by the General Dynamics

Table 1: Synthesis Program System Options

Option Number	Class 1 Station	Class 2 Station	Direct Station	Example
1	Xmit	-	Rcv	Direct Broadcast
2	Xmit	Rcv	-	Redistribution Broadcast
3	Xmit	Rcv	Rcv	Direct & Redistribution
4	Xmit /Rcv	-	-	Single Level Information Transfer
5	Xmit /Rcv	-	Rcv	Single Level Information Transfer & Direct Broadcast
6	Xmit /Rcv	Rcv	-	Single Level Information Transfer & Redistribution Broadcast
7	Xmit /Rcv	Rcv	Rcv	Single Level Information Transfer, Direct & Redistribution Broadcast
8	Xmit /Rcv	Xmit /Rcv	-	Dual Level Information Transfer
9	Xmit /Rcv	Xmit /Rcv	Rcv	Dual Level Information Transfer & Direct Broadcast

Table 2: Ground Stations Cost Model

Subsystem	Unit Recurring	Installation	Operations	Maintenance
Building	X			X
Terminal Equipment	X	X	X	X
Transmitters	X	X	X	X
Receivers	X	X	X	X
Antennas	X	X		X
Standby Power	X	X		X
Test Equipment	X			
Installation & Checkout		X		
Personnel			X	

Corporation. However, the appropriate parameters that determine the costs of all subsystems are included in the program input and can easily be changed. This allows cost changes due to improvements in the technology base to be reflected in the program without the need for modifying the program itself. It also allows any of the subsystems to be eliminated from the system by merely setting their cost coefficient equal to zero.

2.2.2.1.1 Building

This cost is computed only for Class 1 and Class 2 stations. The building is assumed to have 900 square feet for office space and 600 square feet for each transmitter/receiver pair. The cost is assumed to be $39.00 per square foot. Therefore, the cost for the building is:

$$C = (900 + 600\ N_{t/r}) \cdot \$39.00$$

or expressed in millions:

$$C = 0.0351 + 0.0235 \cdot N_{t/r}\ \$\ \text{Million.}$$

The building maintenance cost is 2% of the recurring cost.

2.2.2.1.2 Terminal Equipment

The terminal equipment includes all the equipment needed to interface the receiver system to a ground network. These costs are computed only for Class 1 and Class 2 facilities.

For audio, digital and facsimile data, the price of the multiplexer is $2,000 per duplex circuit. Installation is 100% of unit recurring, operation is 5% and maintenance is 10%.

For video signal, the equipment includes a video tape recorder and a slide film chain. The recurring cost for video terminal equipment is $40,000 for black and white or $120,000 for color, per channel. Installation and maintenance are 10% and operation is 5% of recurring cost.

2.2.2.1.3 Transmitters

Transmitters are included only in Class 1 and 2 models. The transmitter model includes heat exchanger, power amplifier, modulator/exciter, RF control and display and power supply. The transmitter cost is computed from cost curves derived from data from various manufacturers.

2.2.2.1.4 Receivers

Class 1 and 2 receivers are essentially the same. The performance-cost data for Class 1 and 2 receivers are taken from a 1966 study (18) of technical and cost factors affecting television reception from a synchronous satellite for NASA, with some discrepancies corrected.

The Class 1 and 2 receiver models include operation cost of 5%, maintenance of 10%, and installation cost of 15% of recurring costs.

The cost for direct receivers is expected to be considerably less because of the mass production involved. The basic receiver cost is for a single channel receiver and is based on 1000 units per year production. The computation of the cost for multi-channel receivers is as follows. Additional channels are considered in blocks, a block being one channel for FM and 3 channels for AM. There is an increment

of cost for the first additional block of channels and a different cost increment for each additional block of channels after the first.

Class 1 and 2 receivers benefit from a manufacturing learning curve of the form:

$$\frac{C_N}{C_1} = \frac{N^{\log_2 K+1} + \log_2 K}{N(\log_2 K+1)}$$

where N = number of units produced

K = learning factors

This gives the individual unit cost for large production relative to the unit cost for single unit production. A graph of this function for K = .85, .89, .95 is given in Figure 7. For Class 1 and 2 receiver K was chosen as 85%.

The mass production reduction (1000 units/year) for direct class receivers is of a different form:

$$\frac{C_N}{C_{1000}} = 10^{(A_1 + A_2 N + A_3 N^2)/10}$$

where N = 10 log (number of units)

A_1, A_2, A_3 = inputs to the model

The cost increments for additional channels are also computed from curves based on the number of units produced.

2.2.2.1.5 Antenna

There are three types of antennas considered in the ground system model.

1) Steerable parabolic antenna. This is a mechanically steerable, high gain antenna. The cost includes feeds and the mechanical drive.

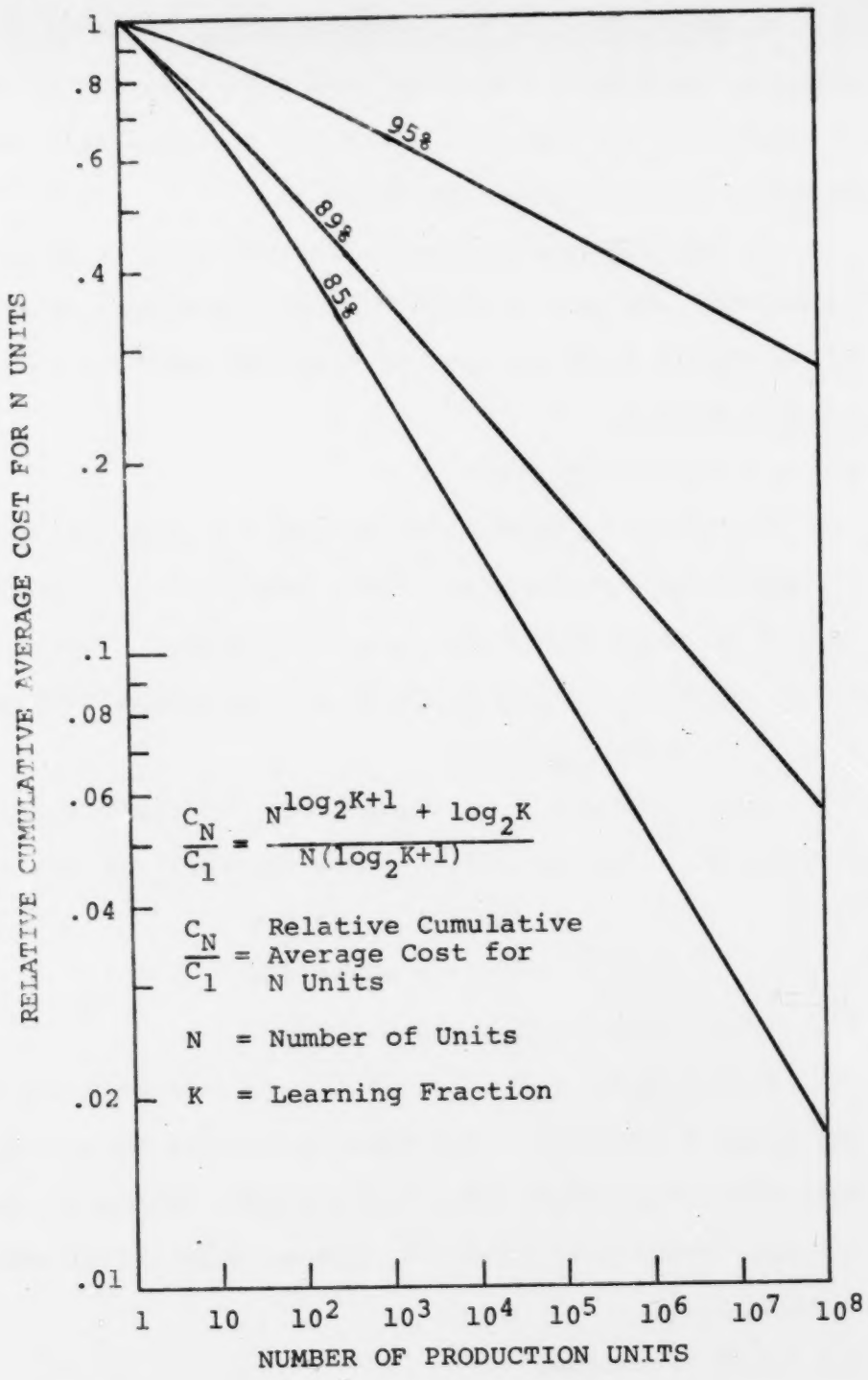


Figure 7: Manufacturing Learning Curves

2) Non-steerable parabolic antenna. This is a moderate sized antenna with a broader beam such that any minor deviation of the satellite from its position will not significantly degrade system performance.

3) UHF wideband antenna. This is again a non-steerable, relatively low gain antenna. As in the type 2 antenna a 95% learning curve is used to find the cost for mass produced antennas.

2.2.2.1.6 Standby Power

The ground system model includes a power generator as an emergency power source. This generator is assumed to have a 1% power efficiency transfer factor. The annual maintenance is assumed to be 5% of the acquisition cost.

2.2.2.1.7 Test Equipment

Test equipment is included only for Class 1 and Class 2 stations. This is a fixed cost for each station:

Class 1 - $50,000

Class 2 - $25,000

2.2.2.1.8 Installation and Checkout

Installation and checkout is included only for Class 1 and Class 2 stations. The cost is assumed to be 15% of the combined acquisition costs for terminal equipment, transmitters, receivers, antennas, transmission lines and standby power.

2.2.2.1.9 Personnel

The number of men required to operate the ground station is given as:

$$N_{men} = 2 \cdot (N_{t/r})^{0.5}$$

The cost is $15,000 per man per year with a 10% increase for second shift and 20% increase for third shift. The total personnel cost is then:

$$C_p = .03 \cdot (N_{t/r})^{0.5} \text{ \$Million for 1 shift}$$

$$= .063 \cdot (N_{t/r})^{0.5} \text{ \$Million for 2 shifts}$$

$$= .099 \cdot (N_{t/r})^{0.5} \text{ \$Million for 3 shifts}$$

2.2.3 Satellite Systems

The satellite system model includes all of the subsystems of the satellite. These subsystems include power subsystems, antennas, receivers, transmitters, multiplexers, structural subsystems, thermal control, stabilization subsystems, telemetry and command subsystems and any manned provisions if they are required.

The costs computed are the acquisition cost and the R and D costs. Operation and maintenance costs do not apply to the satellite model since all costs are incurred prior to operation of satellite.

The various launch vehicles impose different constraints on the satellite in terms of weight, volume and diameter. These constraints are reflected in the model in terms of choice of rigid or expandable antenna, attitude control moment arms and solar array mounting.

In order to size the various satellite size dependent subsystems an iterative procedure is used. First the weight,

volume and power of the independent subsystems is computed. These include the transmitter, receiver, antennas, telemetry and command. The weight, volume and power requirements of these systems are fixed and do not change throughout the procedure. An initial estimate is made for the weight, volume and power requirements of the other systems; attitude control, stationkeeping, thermal control and the structure. The weight, volume and power of the power subsystems is calculated taking into consideration the efficiencies of the subsystems involved. A new estimate of the weight and volume of structure is calculated such that it contains all the equipment. New thermal control, attitude control and stationkeeping requirement are determined and these subsystems are sized. New values for the weight, volume and power of the subsystem are calculated and the process repeats until the change in prime power requirements is sufficiently small. A flowchart of the process is shown in Figure 8.

There are other cost elements involved that are not included in the actual in-orbit hardware. These include a prototype, assembly and checkout integration and management and ground support equipment. These items are all included in the satellite systems model.

There are eight possible launch vehicles which may be chosen for any case under consideration. The original GD/C program included SLV-3A/Agena, SLV-3C/Centaur, SLV-3X/Centaur, SLV-3X/Centaur III, Titan 3C, Titan 3C/Centaur,

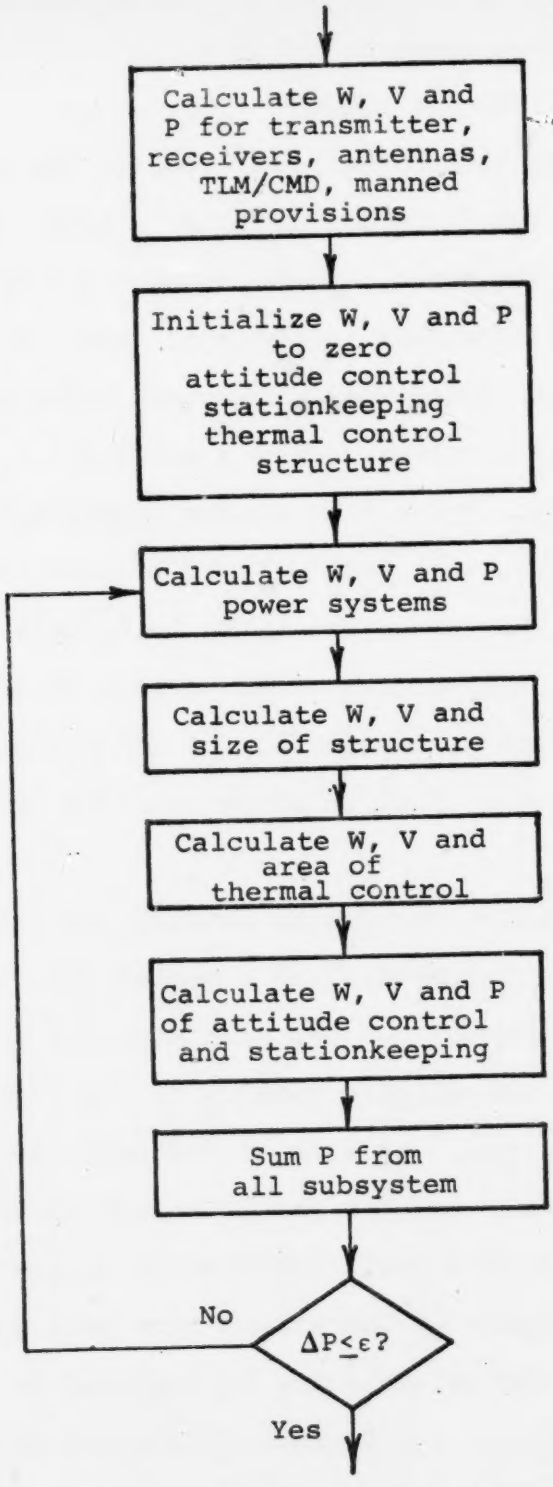

Calculate W, V and P for transmitter, receivers, antennas, TLM/CMD, manned provisions
Initialize W, V and P to zero attitude control stationkeeping thermal control structure
Calculate W, V and P power systems
Calculate W, V and size of structure
Calculate W, V and area of thermal control
Calculate W, V and P of attitude control and stationkeeping
Sum P from all subsystem
No
ΔP≤ε?
Yes

Figure 8: Iterative Procedure for Sizing Satellite Subsystems

Saturn I/Centaur, and Saturn V. These have since been updated to those shown in Table 3.

2.3 OPTIMIZATION TECHNIQUE

The optimization technique used in the program is a steepest descent iterative routine. There are two to four independent parameters, depending on the case being considered, and 78 dependent parameters. The independent parameters are ground station antenna diameters and ground receiver noise figures. Table 4 shows the possible system configurations. Table 5 shows the independent parameters for each configuration while Table 6 shows the dependent parameters. The subscripts 1, 2, 3 indicate Class 1, 2 or direct class, respectively. The choice of whether Class 1 or Class 2 antenna diameter is the independent parameter is made on the basis of which class requires the largest value for C/N.

The optimization routine accepts the initial vector of independent parameters and computes the vector of 78 dependent parameters. A check is made for boundary violations and an optimal perturbation of the independent paraeters is computed. This new independent parameter vector is then used to compute a new dependent parameter vector and the process repeats until convergence is reached or until the maximum number of iterations have been reached.

The optimum perturbation is computed in the following manner: if there is a boundary violation on the dependent parameter vector, Y, the element that violates its constraint

Table 3: Launch Vehicles

Launch Vehicle	Shroud Diameter (ft)	Shroud Volume (ft^3)	Payload (pounds)	Acquisition Cost (millions)	Engineering Cost (millions)
Delta 2914	7.0	400	610	6.4	1.0
SLV-3A/Agena	4.5	500	500	9.1	0.9
SLV-3A/Ascent Agena	9.0	1400	635	9.1	1.1
SLV-3A(u)/Ascent Agena	4.5	500	810	9.1	1.1
Titan IIIB/Centaur/Burner II	9.0	1170	1800	14.4	5.0
Titan IIID/Burner II	9.0	1170	2800	18.8	2.2
Titan IIIC/Burner II	9.0	1170	3800	23.3	3.0
Titan $IIIC_7$	9.0	3160	4500	23.9	2.9

Table 4: System Configurations

Option Number	Class 1 Station	Class 2 Station	Direct Station
1	Transmit	-	Receive
2	Transmit	Receive	-
3	Transmit	Receive	Receive
4	Transmit/ Receive	-	-
5	Transmit/ Receive	-	Receive
6	Transmit/ Receive	Receive	-
7	Transmit/ Receive	Receive	Receive
8	Transmit/ Receive	Transmit/ Receive	-
9	Transmit/ Receive	Transmit/ Receive	Receive

Table 5: Independent Parameters

Option Number	X(1)	X(2)	X(3)	X(4)
1	D_1	D_3	Nf_3	-
2	D_1	D_2	Nf_2	-
3	D_1	D_2	Nf_2	Nf_3
4	D_1	Nf_1	-	-
5	D_1	Nf_1	Nf_3	-
6	D_1 or D_2	Nf_1	Nf_2	-
7	D_1 or D_2	Nf_1	Nf_2	Nf_3
8	D_1 or D_2	Nf_1	Nf_2	-
9	D_1 or D_2	Nf_1	Nf_2	Nf_3

Table 6: Dependent Parameters

Option Number	Y(1)	Y(2)	Y(3)	Y(4)	Y(5)-Y(28)	Y(29)-Y(52)	Y(53)-Y(76)	Y(77)	Y(78)
1	Wt	Vt	Vem	Pps	Ptrs	-	-	-	-
2	Wt	Vt	Vem	Pps	Ptrs	-	-	-	-
3	Wt	Vt	Vem	Pps	Ptrs	-	-	D_3	-
4	Wt	Vt	Vem	Pps	Ptrs	Pg_1	-	-	-
5	Wt	Vt	Vem	Pps	Ptrs	Pg_1	-	D_3	-
6	Wt	Vt	Vem	Pps	Ptrs	Pg_1	-	D_1 or D_2	-
7	Wt	Vt	Vem	Pps	Ptrs	Pg_1	-	D_1 or D_2	D_3
8	Wt	Vt	Vem	Pps	Ptrs	Pg_1	Pg_2	D_1 or D_2	-
9	Wt	Vt	Vem	Pps	Ptrs	Pg_1	Pg_2	D_1 or D_2	D_3

Wt = total satellite weight
Vt = total satellite volume
Vem = volume of satellite equipment module
Pps = satellite prime power supply
Ptrs = satellite transmitter power
Pg_1 = Class 1 transmitter power
Pg_2 = Class 2 transmitter power
D_1 = Class 1 antenna diameter

by the greatest amount is determined. If there were no boundary violations on the previous iteration and there is at least one on the present iteration, the system parameters are returned to their previous values so that a new perturbation can be computed accounting for the boundary information. The routine then computes the optimum perturbation according to the following formula:

$$\overline{\Delta X} = -K_c[I - \phi(\phi^T\phi)^{-1}\phi^T]g - K_y\phi(\phi^T\phi)^{-1}\Delta y_j$$

where ϕ is the constraint gradient

g is the cost gradient

K_y is an arbitrary constant

K_c is a constant computed by the program

j indicates the component which violated its boundary by the greatest degree

Δy_j is the distance from boundary to the element.

If there are no boundary violations the perturbation reduces to

$$\overline{\Delta X} = s \cdot \hat{g}$$

where $\hat{g}$ indicates the unit vector in the direction of $\overline{g}$ and s is a scaling vector.

The scaling vector is included in order to speed convergence. The magnitude of the step size is determined by the program according to the following rules. If successive steps have been in the same direction then the step size should be increased in order to approach the optimal solution more quickly. If, however, the successive steps have been in

opposite directions then one is oscillating about the solution and the step size should be reduced.

Figure 9 shows the values of some of the system parameters for a typical run. The independent variables are the Class 1 antenna diameter, the Class 1 receiver noise figure and the Class 3 receiver noise figure. At the first iteration, the satellite weight was computed to be 3350 pounds. This constitutes a boundary violation since the launch vehicle payload is 2800 pounds. The program then tries to reduce the weight of the satellite by increasing the ground system performance. This is evidenced by the increase in Class 3 antenna diameter and the reduction in Class 1 receiver noise figure. At the second iteration, the satellite weight is reduced but the system cost has increased. The program then determines that the Class 3 antenna diameter must be reduced to reduce the cost, but, then, the Class 3 receiver noise figure must also be reduced to maintain the signal quality. At the third iteration it can be seen that the cost is reducing as well as the satellite weight. This process continues until the system cost can no longer be reduced.

2.4 PROGRAM OUTPUT

The program provides two types of output. The first is a summary provided at each iteration and the second is a comprehensive printout at the end of each case.

The iteration summary provides system independent and dependent parameters, the number of boundary violations and

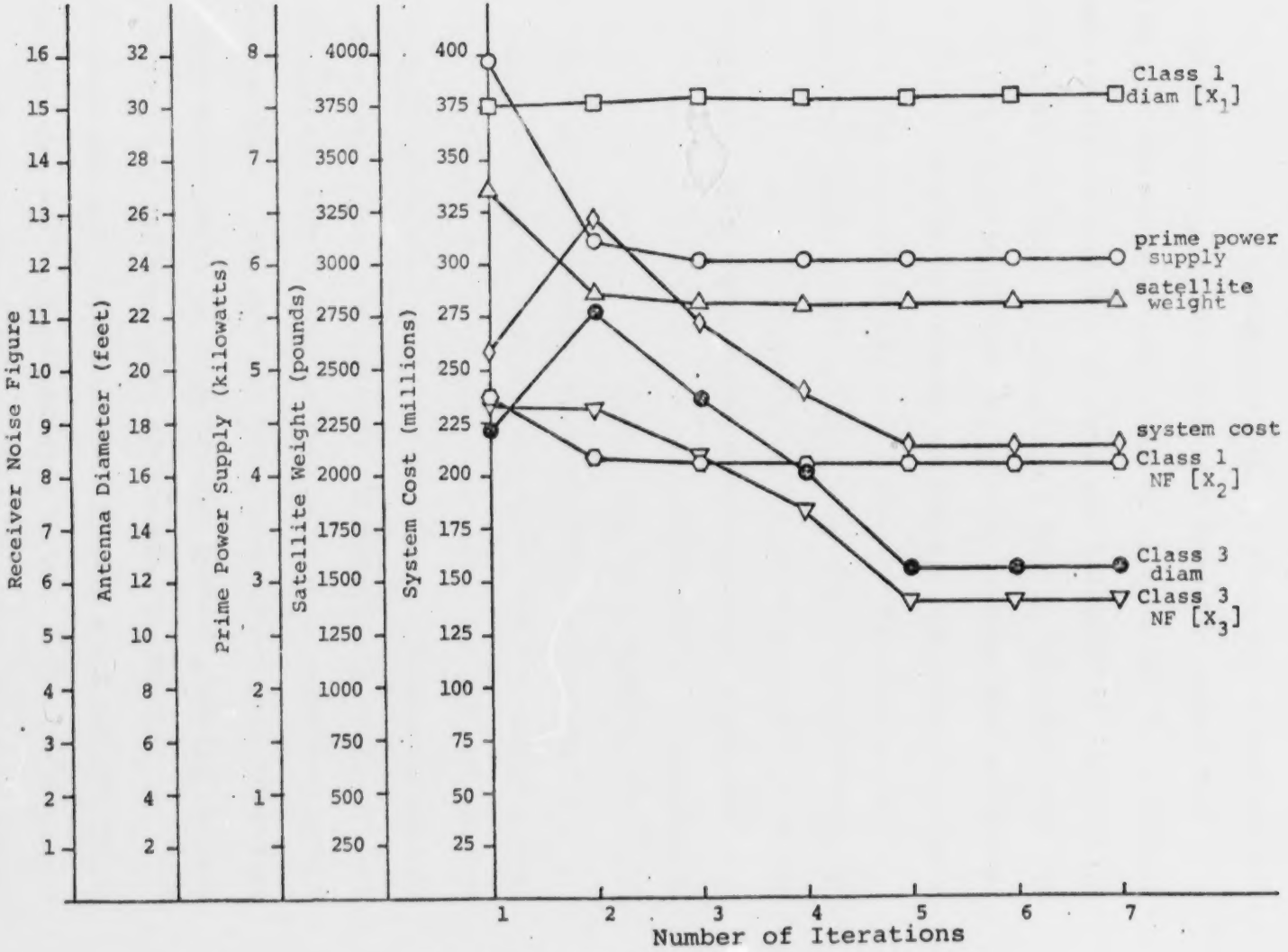


Figure 9: Typical AMP Convergence

various convergence information. It is intended to provide the user with an indication of the state of the system at any iteration and the rate of convergence.

The formal printout for each case is a complete description of the optimal system. The description includes performance information for each ground station class, beam and data for each ground station class, beam and data type, satellite transponder and antenna characteristics and a summary of uplink and downlink losses and noises.

The ground station costs are displayed for each element of the system on a per year basis. These costs are displayed for each ground station class and beam.

The cost, weight and volume of each of the satellite subsystems is printed out.

2.5 IMPLEMENTATION ON IBM 360/65

The program was originally written for use on a CDC 6400 computer. Some modifications must be made to adapt it for use on IBM 360. The word length on the CDC 6400 is 60 bits/word while on IBM 360 it is 32 bits/word. Since some parts of the system are sensitive to small perturbations, double precision variables must be used. This substantially increases core requirements and the IBM 360 linkage-editor overlay feature becomes advantageous to conserve storage.

The individual subroutines were compiled and stored in object format in a partitioned data set. The compiled subroutines were then linked together to form the program load module which is executed each time the program is run.

Being in a previously compiled form, a considerable amount of CPU time normally spent compiling the program is saved each time the program is run. This also aids in subroutine changes. When a modification is necessary to a subroutine, the changes can be made and the subroutine compiled and replaced in the subroutine library. A new load module is then created and replaces the old one. This procedure eliminates the need to recompile the whole program when a change is confined to a single subroutine.

2.6 DEFICIENCIES OF THE GD/C PROGRAM

The program is lacking some very important practical considerations in its economic model. The program computes the system cost in dollars, but this is not the value of the system. The value is a function of interest rate, inflation rate and system lifetime. In order to make reasonable comparisons between two or more systems the cost of each should take into account the time value of money and should be expressed in terms of the present value.

The present value of the system will not be a simple function of the total system cost computed in the GD/C program since some part of this cost represents an initial expenditure for acquisition, installation, R and D and launch of the various subsystems while the other part of the cost is composed of yearly expenditures for operation and maintenance.

Also, the program assumes in its costing models that at the time of system startup all ground stations are built

and operating. It seems rather impractical to assume that the system suppliers would wait for the last of the ground stations to be built before putting the rest of the system into operation. Some sort of growth curve should be included for the ground system costing to account for the fact that all "initial expenditures" will not be expended at the time of system startup. These "delayed initial expenditures" should be accounted for in the total system cost using the time value of money principle.

Another section of STAMP that needs modification is in the modeling and costing of the receive chains for Class 1 and 2 stations and the direct-chain performance-cost data used in STAMP is primarily derived from a 1966 study for NASA (18) and needs updating to reflect the advancements in technology since then. The program assumes that in Class 1 and 2 ground stations there is a separate receiver for each carrier that is received. Also, the direct broadcast receivers modelled in the program are for home viewing and not the community reception type that are likely to see service in the near future. Today's technology certainly permits use of wideband front-ends for receivers in all three classes of stations defined in STAMP with incremental cost for additional channels confined to the channel separation network and individual down converted carrier processing chains. As far as direct broadcast services are concerned, the technology is only at a point where services to relatively small terminals for community viewing

or limited redistribution are feasible. With the 1971 Wired Administrative Radio Conference (WARC) recommendation that Frequency Modulation (FM) be used in 620-790 MHz UHF band for direct television broadcast from satellites and the concentration of interests towards wideband FM systems in 2.5 GHz as well as 12 GHz frequency bands from the viewpoint of near-term feasibility, the need for an Amplitude Modulation (AM) option no longer exists.

The spacecraft model has a provision for a separate antenna system for each beam. In many cases it is desirable to consider generation of multiple beams from a single reflector through an array of feeds. An option for generation of multiple beams from a reflector with an array of feeds needs to be included in the spacecraft model along with the existing provision of an array of antennas for multiple beam generation. Also, STAMP allows for only six beams from a single spacecraft. From the viewpoint of regionalized services, it is often required to have U.S. coverage via as many as eight sub-national beams. Towards this end, the six beam capability of STAMP needs to be extended to a minimum of eight.

Finally, the model for the communication link attenuation in STAMP is incomplete since it does not include the effects of ionospheric scintillation at microwave frequencies present in the vicinity of the geomagnetic equator. Although ionospheric scintillation is an intermittant phenomenon, it must be included in the loss terms for a complete analysis,

particularly for satellite systems serving regions of earth in the vicinity of the geomagnetic equator.

3. MODIFICATIONS IN THE GENERAL DYNAMICS/CONVAIR (GD/C) COMMUNICATION SATELLITE SYSTEM SYNTHESIS PROGRAM

3.1 REVISED SPACECRAFT ANTENNA MODEL

The model contained in the GD/C program defines a separate antenna system for each beam. A modification has been made to allow the system designer for opting the generation of multiple beams from a single paraboloidal reflector with multiple point-source feeds. Of course, there are many ways of generating multiple-beams--from multiple-feed paraboloidal reflectors and spherical reflectors to phased arrays, multiple-feed waveguide lenses and dielectric lenses. Indeed, a recent Lockheed Missile and Space Company study of multibeam antennas for NASA has recommended a two-antenna circular aperture artificial dielectric lens configuration from the viewpoint of spot-beam coverage, beam-to-beam isolation and other desirable characteristics of the multiple beam application.(13) We have only added multiple-feed paraboloidal reflector option because at present it seems to be a popular concept and because weight-size-performance data was readily available.

The spacecraft antenna is modeled in subroutine ANTS. The inputs to the subroutine are the antenna orthogonal diameters for each beam, the equivalent antenna diameter for each beam ($= \sqrt{d_1 d_2}$), the diameter breakpoint to determine if the antenna is rigid or expandable and the cost, weight and volume coefficients for the antenna and feedbooms.

The original model determines whether each antenna is rigid or expandable on the basis of the launch-vehicle shroud diameter constraints and the antenna diameter and computes the weight, volume and cost of each antenna feed-boom combination. It then sums these values to get the total weight, volume and cost of the antenna subsystem.

The modified model determines whether the antenna is rigid or expandable on the basis of the maximum diameter and computes the weight, volume and cost of a single antenna of that diameter and a feedboom for each beam. These are then the weight, volume and cost of the entire antenna subsystem.

The new model has the flexibility of being able to model a number of different types of antennas rather than just a reflector type. By manipulating the input coefficients that determine cost, weight and volume, a variety of antennas can be sized and costed.

3.2 INCREASED BEAM CAPABILITY

Another modification to the original GD/C program extended the capability from a maximum of six beams per satellite to eight beams. This was done to allow for greater regionalized coverage as might be needed in an educational system. It also provides the capability to reach more areas but more importantly it increases the capability, using narrow beams, to more precisely define the shape of the larger coverage areas so as to reduce the amount of

energy falling outside the desired areas while maximizing the amount of energy radiated to the target area. The implementation of this modification in the GD/C program was rather trivial in nature but time consuming. The size of several arrays in various subroutines was expanded to accommodate the extra beams.

3.3 AM SECTION REMOVAL

The fact that satellite communication systems are power limited indicates that the preferred modulation techniques are those employing bandwidth expansion. With this in mind and the popularity of frequency modulation in present systems, the amplitude modulation capability was removed from the program. This amounted to a removal of the modulation option and the AM performance and costing sections of the program. The elimination of these sections helped offset the increased memory requirements caused by the six to eight beam modification.

3.4 MULTI-CHANNEL RECEIVERS

In the costing section of the ground facility subroutine for Class 1 and Class 2 facilities, a separate receiver is assumed for each carrier received by that facility. Present technology indicates that systems built in the near future will use multi-carrier receivers, i.e., receivers with a wideband front end that will handle multiple TV or other carriers simultaneously. This will eliminate the need for the separate receivers and will reduce the system cost accordingly. A change in the program was made to incorporate

this upgraded technology. The change was made in the Class 1 and 2 ground facility model. In the original program the unit cost of a single receiver was computed and multiplied by the number of channels received at each class facility (1 or 2) for each beam.

In the modified version the unit cost for a receiver with a wideband front-end is computed. A cost increment for the channelization based on the number of channels received (an input to the subroutine) is added to the wideband receiver costs. The program is written to allow for differences in the number of channels received by wideband front-ends in each beam. However, in all cases, simultaneous demodulation of all channels is assumed unlike the receivers to be used in ATS-F Health-Education Telecommunication (HET) Experiment where only one of the two channels could be demodulated at a given time. The receiver unit cost, the sum of the wideband front-end and channelization costs, is multiplied by the proper learning factor to give the unit cost of the multi-channel receivers for each class facility and for each beam under mass production.

3.5 DIRECT CLASS RECEIVER MODEL

The direct class receiver model in the original program is intended for small, lower quality, mass produced receivers suitable for direct to home TV broadcast and, as such, the receiver costing is treated differently from Class 1 and Class 2 systems which could have receive as well as transmit capability. The receiver cost in the original GD/C program

is composed of, basically, three elements: a basic receiver cost, a cost for the first additional block of channels, and a cost for all additional blocks after the first. A block of channels is defined as three channels for AM and one channel for FM. In addition, if a combination of AM and FM is used there is an additional cost increment. The receiver cost is then sum of all these elements.

This direct receiver model as well as the method of costing was determined to be unrealistic. It assumed direct-to-home satellite broadcast and complicated the modifications in the input costing coefficients. The direct (Class 3) receiver costing has been modified to agree with the Class 2 receiver costing and reflect the broadcasting to community headends, that is, a basic wideband receiver cost is determined, an increment cost per extra channel is added to it to reflect channelization costs and the result modified by the learning factor.

3.6 SCINTILLATION LOSS MODEL

Until recently, signal attenuation due to ionospheric scintillation was thought to be negligible above 1 GHz. However, in the fall of 1969 several stations in the Indian Ocean region using an INTELSAT satellite reported signal fluctuation which could not be attributed to equipment malfunction in either the ground station or the satellite. Further monitoring showed effects that were highly correlated with ionospheric activity at equatorial latitude.

This indicated that the scintillations were caused by electron density irregularities in the ionosphere.(10)

In 1970 monitoring was begun at a number of earth stations in the INTELSAT system. After some 15 months the monitored data was collected and analyzed. It was found that scintillation is an intermittant phenomenon that both enhances as well as attenuates the signal level. This indicates that the effect is not caused by an absorptive mechanism. The monitoring was done at 6 GHz. Taur (10) recommends use of λ^2 (λ = wavelength of transmission) dependence to obtain approximate corresponding amplitude distribution at frequencies other than 6 GHz. However, at frequencies below 2 or 3 GHz, the λ^2 dependence doesn't seem valid.*

The scintillation activity shows a strong seasonal dependence. This dependence is stronger at the equator than at the higher latitudes. The activity is greatest during the vernal and autumnal equinoxes and the autumnal peak is generally larger than the vernal peak.

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*In technical circles, in absence of scintillation data at microwave frequencies other than 6 GHz, there is considerable skepticism about using either λ^2 or λ dependence. ATS-5 propagation experiments are not going to resolve the question because of the spin-modulation of the signal by spin of the satellite originally intended to be fully stabilized. Resolution of the order of the λ dependence is likely to come from ATS-F and CTS propagation and user experimentations.

The scintillation activity peaks at about 2000 hours local time at all stations. This is approximately sunset in the ionospheric region. One theory behind this is that as the sun goes down the ionization source disappears allowing ions and free electrons to combine. As these combinations take place the ionosphere becomes "patchy." As the time passes these patches become smaller until they do not affect the higher frequency transmission but are still noticeable in the VHF bands.

The dependence of scintillation on latitude is not clear although it seems to be confined to $\pm 30^{\circ}$ geomagnetic latitude.

The scintillation loss model that was added to the program was based on the data from the COMSAT study.(10) The scintillation is modeled in six geomagnetic latitude bands between 30°N. and 30°S. One of the INTELSAT ground stations included in the study was chosen from each latitude band as typical of that band. The relative amplitude distribution curve was obtained from the COMSAT study. An example of this type of curve is shown in Figure 10. These curves were then approximated in three pieces with a linear expression of the form:

$$A_1 + A_2 X$$

where $X = \log P$

$$P = 100 - POR$$

POR is the input to the model and is the scintillation

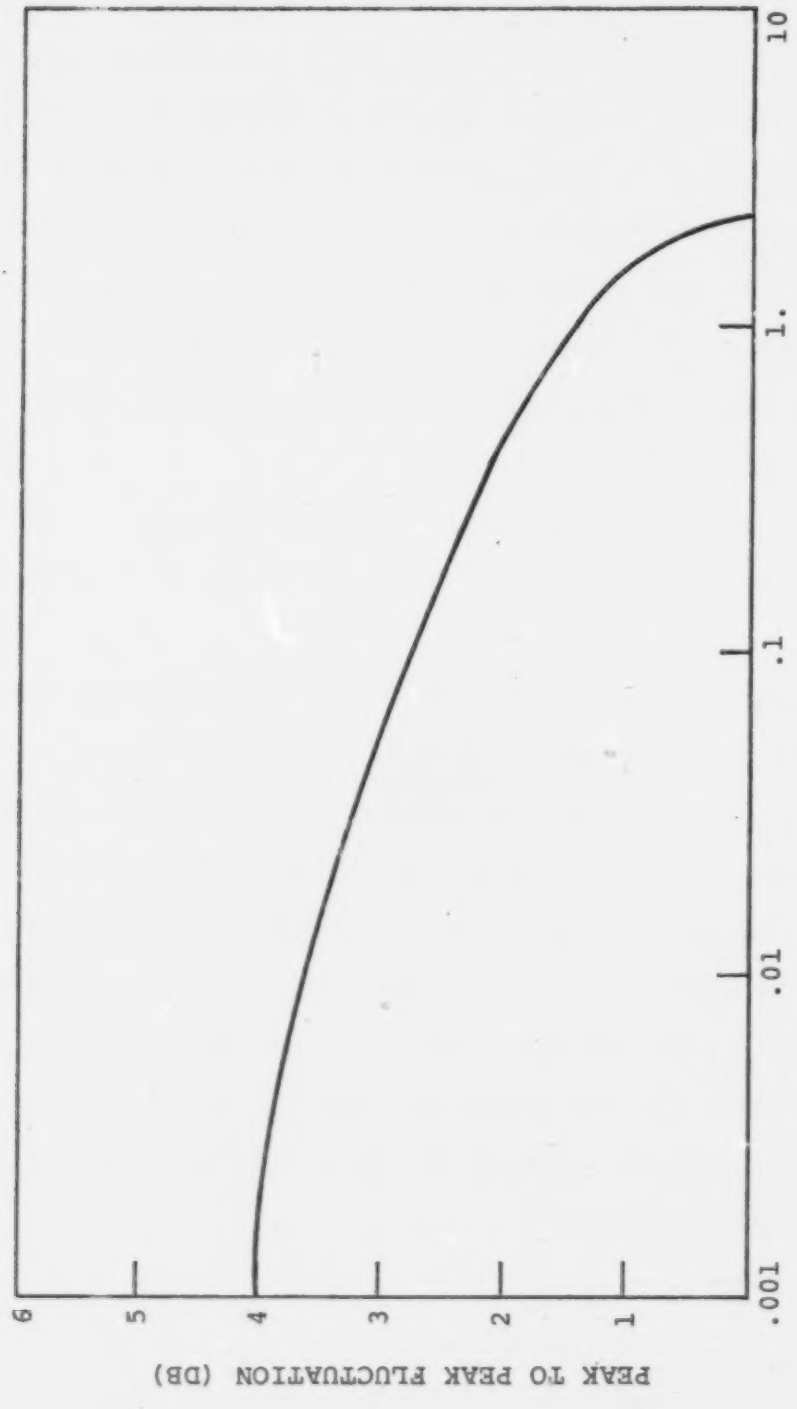


Figure 10: Amplitude Distribution at Ascension Island at 6 GHz (10)

probability. The output of the model is the peak signal fluctuation at 6 GHz that will not be exceeded POR percent of the time.

The first step in the model is to determine the geomagnetic latitude of the beam center. This is determined from the following relationship:

$$\sin \Phi = \sin \phi \cos 11.7° + \cos \phi \sin 11.7° \cos(\lambda - 291°)$$

where Φ = geomagnetic latitude

ϕ = beam center geographic latitude

λ = beam center geographic longitude

This geomagnetic latitude is then used to determine the proper latitude band in the scintillation model. The loss, at 6 GHz, is then computed from the curve approximations. This value is then modified for the particular frequency in use according to $1/\lambda^2$ for frequencies above 6 GHz. For frequencies above 2 GHz and below 6 GHz, the amplitude distribution of scintillation at 6 GHz is assumed. The scintillation loss is combined with the other losses in the program to determine the total loss.

3.7 SATELLITE AND LAUNCH VEHICLE FAILURE RATES

Under real life conditions the launching of a satellite cannot be given a success probability of 1. Both the spacecraft and the launch vehicle have a finite probability of failure in the process of orbital placement and the initial deployment of the spacecraft. In general, when a failure occurs in placing a satellite in the orbit, the

satellite and launch vehicle must be replaced. These failure probabilities should be reflected in the space segment costing.

The placement of a satellite in the geostationary orbit could be seen as a union of two independent but not mutually exclusive set of events. One is the launch of the satellite and its release either in a transfer orbit or directly in the synchronous orbit which depends on the proper functioning of the launch vehicle. The second is deployment of the satellite after its release from the launch vehicle either in the transfer orbit and its subsequent transfer thereafter to the synchronous orbit or in the synchronous orbit in terms of unfolding of the solar cell arrays and expandable antennae and acquisition of the desired stabilization and orientation. An option has been provided in the modified STAMP for the user to supply appropriate launch vehicle and satellite failure rates to compute a total satellite orbital placement failure rate as follows:

$$FAILR = FAILLV + FAILST - FAILST \cdot FAILLV$$

where, FAILR = satellite orbital placement and deployment failure rate

FAILLV = launch vehicle failure rate

FAILST = satellite failure rate reflecting spacecraft failures after a successful launch and release from the launch vehicle

The costs for the satellite and for the launch vehicle are then modified by the factor (1 + FAILR) to account for the cost of the failure.

3.8 SATELLITE SPARE OPTIONS

Satellites are not only vulnerable to failure at launch and orbit placement but also to failure before their design lifetime expires. When designing a system for very high reliability it may be desirable to include the cost of one or more satellite spares in the system costing. Whether the spare should be in orbit or on the ground depends on the degree of reliability required and the allowable communication link down time.

An option was added to the program to allow inclusion of satellite spares in the system. Any number of orbit spares and/or ground spares can be included. Two constants, C1 and C2, are included and determine the cost of the ground and orbit spares, respectively, relative to the cost of the active satellite. The satellite segment cost then becomes:

$$CST_1[(1 + FAILR) \cdot (NSAT + NOS \cdot C2) + NGS \cdot C1]$$

where CST_1 = the cost of a single active satellite

FAILR = satellite orbital placement

NSAT = number of active satellites

NOS = number of orbit spares

NGS = number of ground spares

The launch vehicle costing is very similar. The only difference being in the fact that, in general, more than

than one satellite can be launched by one launch vehicle.

$$CST_2[(1 + FAILR) \cdot \frac{NSAT + NOS \cdot C2}{NSL} + NGS \cdot C1]$$

where, CST_2 = cost of a single launch vehicle

NSL = number of satellites per launch vehicle

3.9 PRESENT VALUE ANALYSIS AND GROUND FACILITY POPULATION GROWTH

Investing in a communication satellite system generally requires expenditures over a long period of time. Along with the initial costs of R and D and of obtaining and installing the various pieces of hardware, there is an annual cost for operating and maintaining the ground segment.

The original STAMP program calculates the amount of dollars that the system will cost each year. This includes the annual expenses plus the total initial costs amortized over the system lifetime. This is an idealized viewpoint and does not account for the fact that, in the real world, the value of money changes with time due to the effects of interest and inflation. The time value of money states that a dollar on hand today is worth more than a dollar received ten years from today since it can be invested and be earning interest for ten years.

When comparing possible alternative systems or to perform sensitivity analysis it becomes necessary to have a common basis for the value of the expenditures involved. The equivalence of two systems may not be apparent by simply

listing the expenditures. For example, consider two systems, each satisfying the user requirements in different ways. System 1 requires a $150 million initial investment and annual expenditures of $30 million while system 2 requires an initial investment of $400 million and annual expenditure of $10 million. If the lifetime of the system is assumed to be 15 years, then system 1 has an apparent value of 150 + 30 · 15 = $600 million and system 2 has an apparent value of 400 + 10 · 15 = $550 million. Clearly, from this analysis system 2 has a $50 million advantage and would be the logical choice. However, if an interest rate is allowed to enter the picture, the annual expenditure must be discounted to an equivalent amount which will earn enough interest such that the sum of the principle and the interest will be enough to pay the annual costs as they occur. This is known as a present value analysis. Using this type of analysis on the two systems above assuming a 5% interest rate, shows that system 1 has a present value of $461.39 million while the present value of system 2 is $503.79 million. The logical alternative now is system 1 which shows a $42.4 million advantage.

The present value analysis was implemented in the program by changing the costing routines of the space and ground segments. The space segment in the modified program is costed in the following way:

Assume a system lifetime, LSYS, and a satellite lifetime, LSAT. The number of satellite launches, NLCH, is

then the least integer greater than or equal to LSYS/LSAT (Figure 11). At each of these launches a total of NSAT + NOS satellites are launched, where NSAT = the number of active satellites and NOS = the number of orbit spares in the system.

Now if each satellite costs $\$CST_1$ today, then the cost in any launch year k·LSAT is given by:

$$\$CST_1[(1 + FAILR)\cdot(NSAT + NOS\cdot C2)]\cdot(1 + inf)^{k\cdot LSAT}$$

where, FAILR = total system failure rate

C2 = relative cost factor for orbit spares

inf = inflation rate

The cost for that particular launch discounted to the present value is then:

$$\$CST_1[(1 + FAILR)\cdot(NSAT + NOS\cdot C2)]\ (1 + inf)^{k\cdot LSAT} \cdot(1 + int)^{-k\cdot LSAT}$$

where, int = the discount (negative interest) rate.

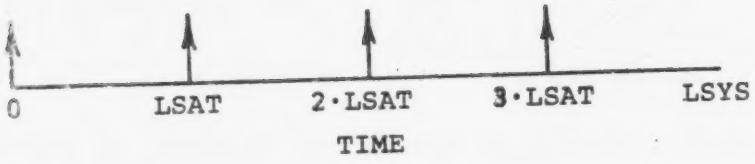
The present value of all the launches is:

$$\$CST_1[(1 + FAILR)\cdot(NSAT + NOS\cdot C2)\cdot \sum_{k=0}^{NLCH-1} \cdot\left(\frac{1 + inf}{1 + int}\right)^{k\cdot LSAT} + NGS\cdot C1]$$

where, NGS = the number of ground spares

C1 = relative cost factor for ground spares

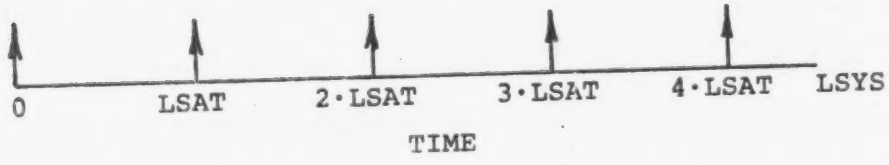
If $\$CST_2$ is the cost of one launch vehicle today, then the present value of the launch vehicles can be determined



i.e. LSYS = 40 years

LSAT = 10 years

NLCH = 4



i.e. LSYS = 45 years

LSAT = 10 years

NLCH = 5

Figure 11: Launch Stream Examples

by a similar analysis. The only difference is in the factor NSL, the number of satellites per launch vehicle,

$$\$CST_2[(1 + FAILR)\cdot\frac{NSAT + NOS\ C2}{NSL}\sum_{k=0}^{NLCH-1}\cdot\left(\frac{1 + inf}{1 + int}\right)^{k\cdot LSAT} + NGS\cdot C1]$$

where, NLCH = number of satellite launches in system lifetime.

The ground segment costing must be considered next. When a system with a large number of ground facilities is being built it seems very possible, if not probable, that all the ground facilities will not be built when the system is started. A good example of this is an educational television distribution system in which there is a single regional facility to transmit educational television to receivers located in the various schools in that region. It is highly probable in this case that the system will begin operation before all the schools have their receiving facility.

Because of the fact that, in general, some of the ground facilities will be acquired in the future, the acquisition costs must be discounted to the present value. Provision must also be made to account for the fact that the annual expenditures for these "late facilities" do not begin until after they are built and operating.

With this in mind, a ground facility population growth curve was incorporated into the program. This allows the user to specify, for each beam and for each class of ground facility, whether or not a growth curve is to be specified and, if so, the appropriate parameters to define the growth. The user specifies the number of years from system startup until the growth is complete, IBLD, the number of facilities available at system startup, FCINIT, and a parameter that describes the rate of growth, β. The general form of the equation is:

$$f(t) = \alpha\varepsilon^{-\beta/t}$$

where $f(t)$ is the earth-terminal population at time t and α is a constant that is computed by the program such that $f(IBLD)$ will equal the maximum number of facilities. Some examples of this type of growth curve are shown in Figure 12 for various values of β with a 10 year growth lifetime. Specifying a non-zero initial facility population, FCINIT, has the effect of shifting the desired curve by an amount T_1 to the left such that the curve intersects the vertical axis at the proper population. T_1 is determined such that $f(T_1)$ = FCINIT (Figure 13). It should be noted that this growth curve is valid only until year IBLD, after that the ground facility population is at its maximum, and for the larger values of β there is a somewhat abrupt discontinuity at year IBLD.

The ground facility costing is divided into two parts, the initial capital investment and the annual operating

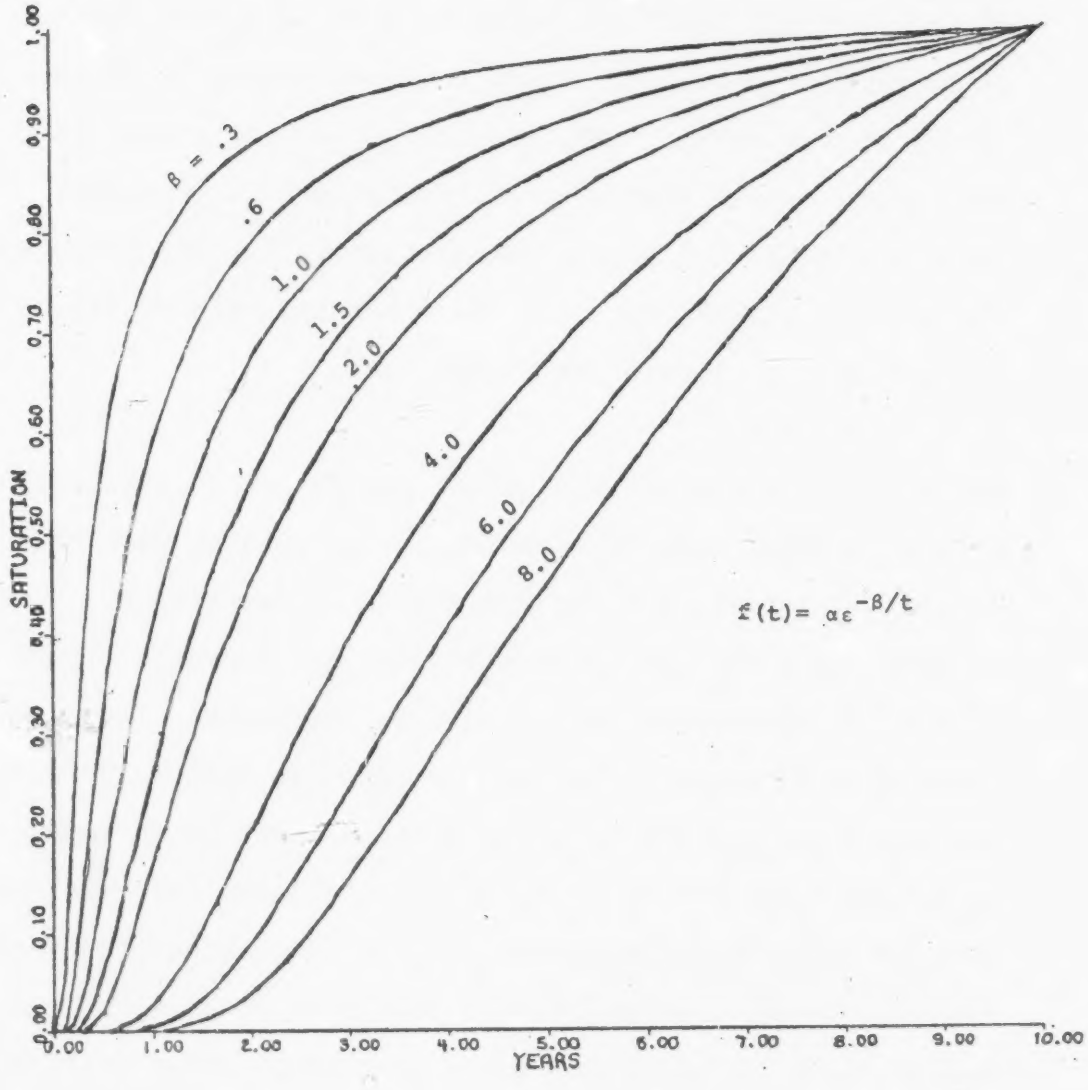


Figure 12: Earth-Terminal Population Growth Curves

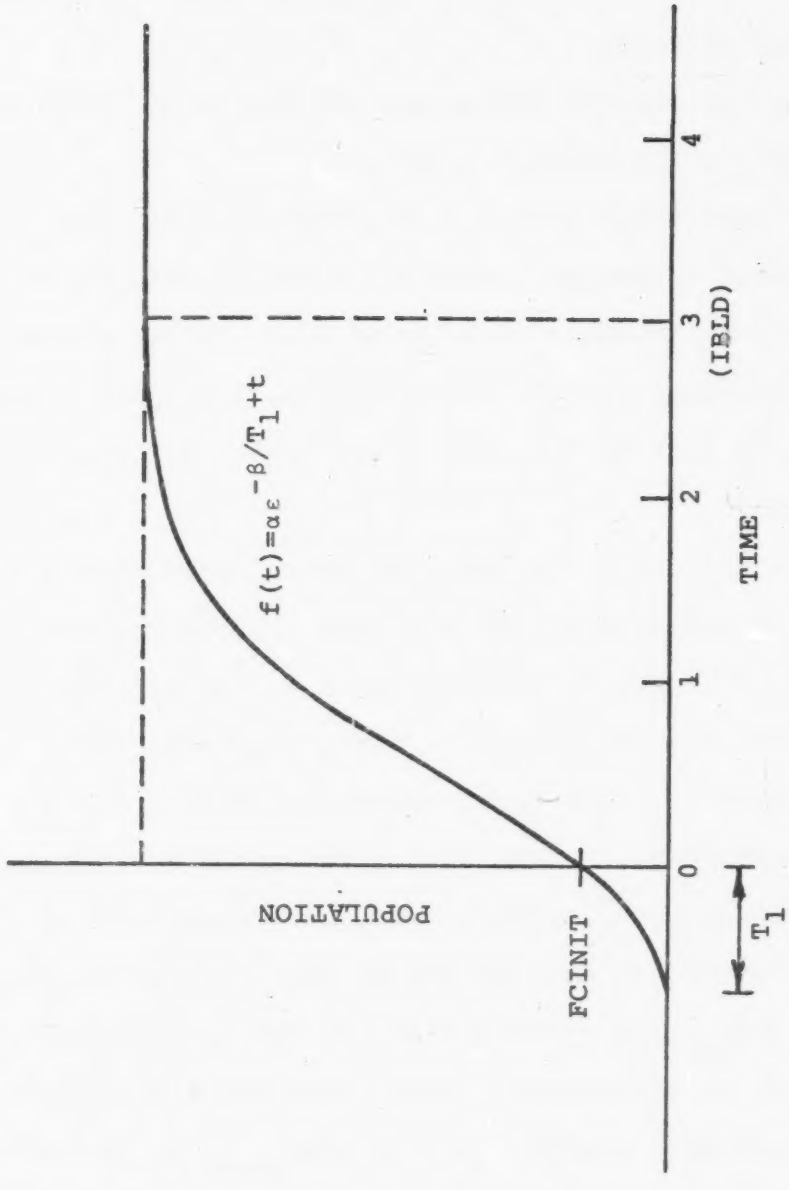


Figure 13: Growth Curve with Non Zero Initial Population

costs. The initial capital investments include the costs of acquisition, R and D, and installation of the ground facilities while the annual operating costs include the costs incurred each year for the operating and maintaining of the ground segment.

The initial capital investment of the ground segment is determined in the following manner.

In the case where there is no growth curves, the initial capital investment amounts to merely the sum of all the acquisition and installation costs of the ground segment. The costs are all assumed to be incurred at the time of system startup so there is no effect of interest or inflation.

On the other hand, in the case where there is a growth curve some of the acquisition and installation cost will be incurred after system startup and the interest and inflation will have an effect on them. Consider the growth curve of Figure 14. The growth starts at FCINIT initial facilities and grows to FMAX facilities in IBLD = 7 years. The growth model in the program is a staircase type of function in which all the facilities built within a year, designated $NFAC_i$, are assumed built at the end of that year as shown in the figure. Under this assumption, the costing is somewhat simplified. If $\$CST_{3init}$ is the initial cost of a single facility today, then the cost of a single facility k years from now is:

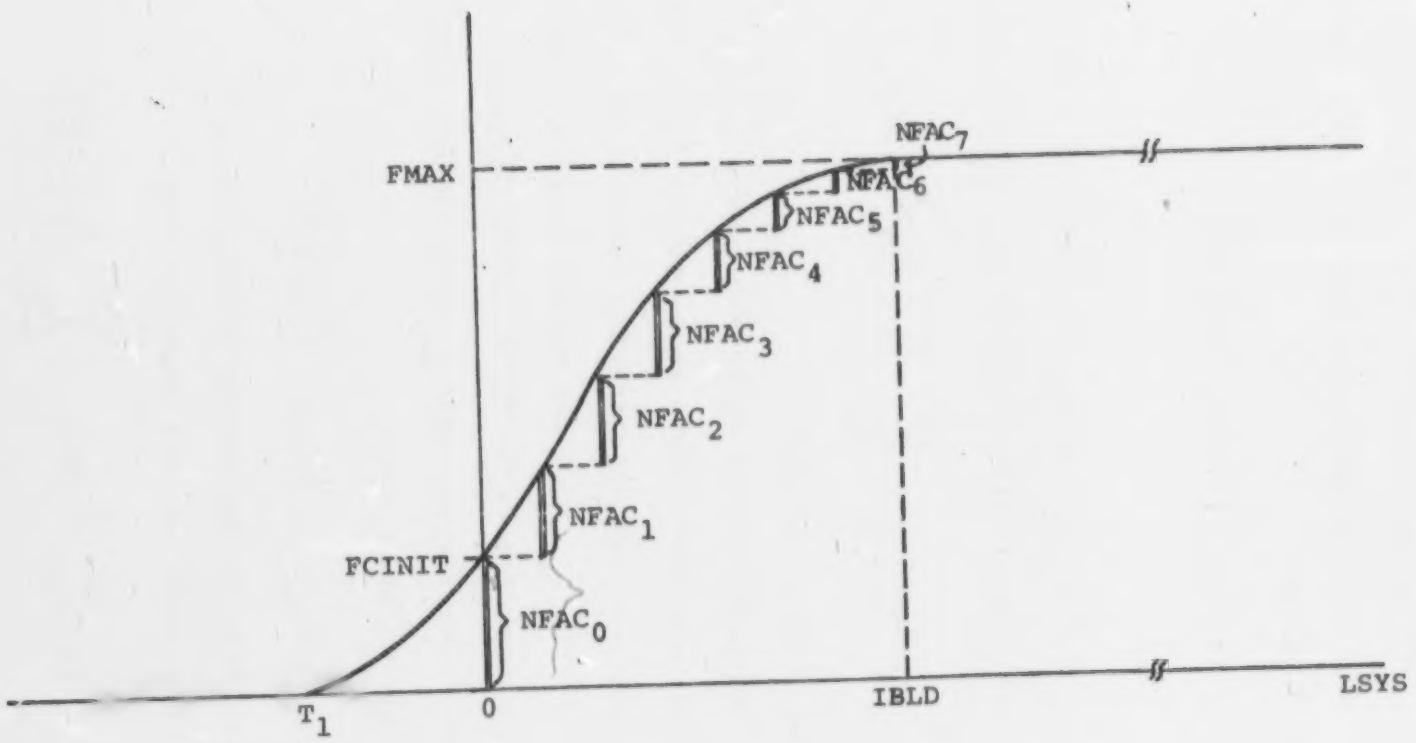


Figure 14: Program Growth Model

$$\$CST_{3init}(1 + inf)^k.$$

The total expenditure for all facilities built within that year is

$$\$CST_{3init} \cdot NFAC_k \ (1 + inf)^k$$

Discounting this value to the present value it becomes:

$$\$CST_{3init} \cdot NFAC_k \ (1 + inf)^k \ (1 + int)^{-k}$$

The total initial ground segment cost becomes:

$$\$CST_{3init} \cdot \sum_{k=0}^{IBLD} \left(\frac{1 + inf}{1 + int}\right)^k \cdot NFAC_k$$

where $NFAC_0$ = FCINIT.

Next the annual operating expenses must be considered. In the case where there is no growth curve, the present value of the annual operating costs is as follows:

If $\$CST_{3ann.}$ is the annual cost, including operating and maintenance cost, for a single facility, then the total annual cost for any year k, inflated and discounted to the present value is then

$$\$CST_{3ann} \cdot FACIL \cdot \left(\frac{1 + inf}{1 + int}\right)^k$$

where FACIL is the number of facilities.

The total for all years is then

$$\$CST_{3ann} \cdot FACIL \cdot \sum_{k=0}^{LSYS} \left(\frac{1 + inf}{1 + int}\right)^k .$$

In the case where there is a growth curve, the annual costing is simplified by computing an equivalent average

number of facilities, FAVG, that would be available from system startup. This is done by determining the area under the facility population curve from the time of system startup to the end of the system lifetime and dividing this by the system lifetime. Using the stepwise model this is done by

$$FAVG = \frac{\sum_{k=0}^{LSYS} NFAC_k \cdot (LSYS - k)}{LSYS}$$

However, since there is no growth after year IBLD, $NFAC_k$ for k = IBLD + 1, IBLD + 2, ... LSYS will be equal to zero. The equation then becomes

$$FAVG = \frac{\sum_{k=0}^{IBLD} NFAC_k \cdot (LSYS - k)}{LSYS}$$

The average annual cost for any year k, inflated and discounted to present value, is then

$$\$CST_{3ann} \cdot FAVG \cdot \left(\frac{1 + inf}{1 + int}\right)^k$$

and the total average annual costs for all years is then

$$\$CST_{3ann} \cdot FAVG \cdot \sum_{k=1}^{LSYS} \left(\frac{1 + inf}{1 + int}\right)^k$$

It should be noted that the manufacturing learning curve used in this cost computation is based on the total number of facilities built rather than on yearly production.

That is, the growth curve for the ground facilities is ignored for purposes of learning curve cost computations.

3.10 GROWTH CURVE PRINTOUT SUBROUTINE

A new subroutine has also been added to the program to display the growth curves. An example is shown in Figure 15. A new input to the program, IGCPLT, allows the user to specify which class of ground facility and which beam is to be displayed. The input IGCPLT, is dimensioned 3 x 8, where the first subscript indicates the ground station class and the second indicates the beam number. If IGCPLT (J, I) is equal to 1, the growth curve for class J in beam I will be displayed; if it is equal to 0, no display will appear for that class and beam. The graph is intended to give only a rough idea of the growth rate and the ground facility population at any given year.

3.11 CHANGES IN OUTPUT FORMAT

Many of the modifications in the original GD/C program necessitated changes in the output routines. For example, the output for each iteration in the original program printed out the power transmitted at the Class 1 and Class 2 ground stations, PG1 and PG2, and at the satellite transponder, PTR, for each data type and for each of the six possible beams (Figure 16). However, in the modified program there are eight possible beams. Since the iteration printout was densely packed as it was, it was necessary to either completely reformat it or do nothing to it and print out the transmitter powers for only the first six beams.

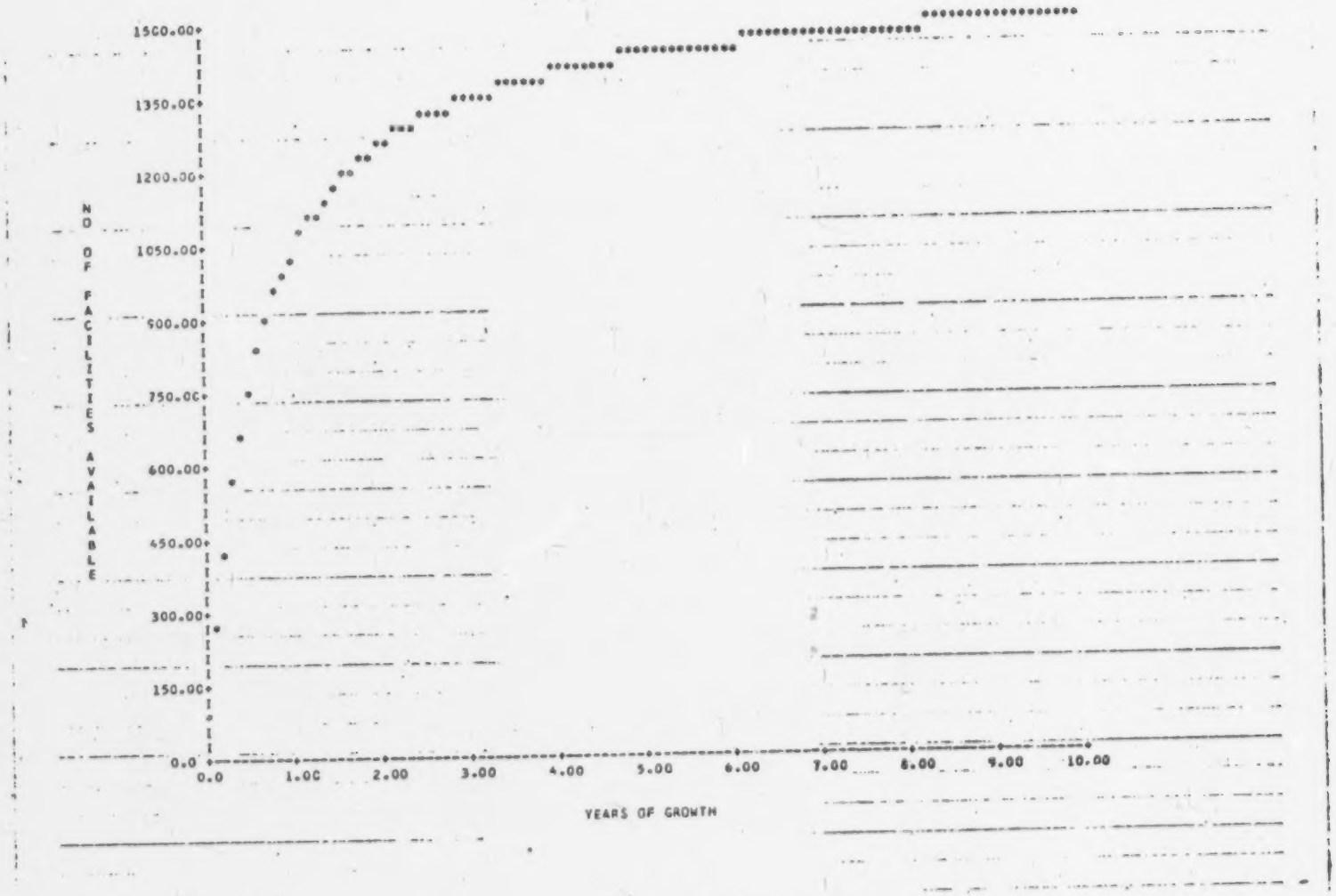


Figure 15: Growth Curve Printout

ITER=	1	PG1=	1730.3	7.8	22.3	0.0	0.0	0.0
WSAT=	2884.7		3841.8	86.6	247.3	0.0	0.0	0.0
VSAT=	250.7		0.0	0.0	0.0	0.0	0.0	0.0
VEM =	66.9		0.0	0.0	0.0	0.0	0.0	0.0
PPS =	7096.3	PG2=	27.5	0.6$	1.8	0.0	0.0	0.0
D(2)=	9.1783		0.0	0.0	0.0	0.0	0.0	0.0
			0.0	0.0	0.0	0.0	0.0	0.0
D(3)=	13.1304		0.0	0.0	0.0	0.0	0.0	0.0

PTR=	79.0	1.5	0.7*	0.0	0.0	0.0
	1721.0	160.3	79.2	0.0	0.0	0.0
	0.0	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	0.0	0.0	0.0	0.0
X=	18.3300	DX= -0.82660	G= -3.2886	S= 1.0000	ICV=0	JCV=1
	4.9900	1.43305	4.9321	1.0000	NBVIOL =	2
	5.1970	-1.39667	-14.4983	1.0000	TOTAL COST=	
	3.5900	0.0	6.3218	1.0000	429.7993	

Figure 16: Individual Iteration Printout

The latter was chosen and justified by the fact that a reasonably good idea of the state of the system at each iteration could be obtained from six beams.

The formal output routines have been modified in a number of ways also. Rather than showing the system costs in terms of millions per year, as in the original program, they are now printed in terms of the present value of the capital investment, the average annual operating cost and the present value of the annual cost over the lifetime of the system (Figure 17). The total capital investment figures are a sum of the acquisition and installation of the ground facilities, including that of the facilities that are built after the system startup inflated and discounted to the present value, and the costs of acquisition and R and D of the satellites and launch vehicle, where the cost of launches after system startup are also inflated and discounted to present value. The average annual operating cost includes operation and maintenances costs of the average number of ground facilities as explained above. The present value of annual operating costs is the sum of the average annual operating costs inflated and discounted to the present value for each year of the system lifetime. The assumed discount and inflation rates are also printed out.

Some new parameters are printed out on the satellite subsystem page of the output (Figure 18). These include the

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PAGE 1

USER REQUIREMENTS

SATELLITE LONG = -120.0 DEG UPLINK FREQUENCY = 14.00 GHZ
SATELLITE LIFE = 5.0 YEARS DOWNLINK FREQUENCY = 11.90 GHZ
TOTAL SYS LIFE = 15.0 YEARS NUMBER OF BEAMS = 3

USER NO	USER DESCRIPTION	RCVR ENVIR	NUMBER OF STATIONS CLASS 1	CLASS 2	DIRECT
03	EDUCATIONAL/INSTRUCTIONAL DISTRIBUTION (3 BEAMS)	URBAN	3.	0.	15000.

USER NO	TOTAL CAPITAL INVESTMENT (PRESENT VALUE IN MILLIONS) TOTAL	CLASS 1	CLASS 2	DIRECT	SPACE SEG	TLM/CMD
03	130.959	1.156	0.0	23.320	105.941	0.543

USER NO	AVERAGE ANNUAL OPERATING COST (IN MILLIONS) TOTAL	CLASS 1	CLASS 2	DIRECT	TLM/CMD
03	2.809	0.340	0.0	2.335	0.134

USER NO	PRESENT VALUE OF ANNUAL OPERATING COST (IN MILLIONS) TOTAL	CLASS 1	CLASS 2	DIRECT	TLM/CMD
03	26.784	3.240	0.0	22.271	1.273

USER NO	DISCOUNT RATE (PER CENT)	INFLATION RATE (PER CENT)
03	10.0	3.5

Figure 17: Partial Formal Output

SATELLITE SUBSYSTEMS	COSTS (MILLIONS) ACQUISITION	R+D	TOTAL	WEIGHT (LBS.)	VOLUME (CU FT)	TYPE	DESCRIPTIVE PARAMETERS
POWER SUBSYSTEM							
PRIME POWER	1.64	0.32	1.75	692.3	115.62	SOLAR	POWER = 4.770 KW
SECONDARY POWER	0.02	0.13	0.06	524.1	4.28	NI-CAD	CAPACITY = 10.228 KW-H
CONDITIONING	0.10	0.20	0.17	249.6	3.34		
DISTRIBUTION	0.24	0.32	0.34	68.0	5.76		
ANTENNA	0.00	0.05	0.02	16.7	8.27	RIGID	DIAM = 2.89, 3 BEAMS
TRANSMITTER	1.16	0.65	1.37	341.2	20.43	TWT	12. TRANSMITTERS
MULTIPLEXER	0.20	0.37	0.32	7.4	0.24	WAVEGUID	
RECEIVERS	0.37	0.26	0.46	105.0	3.52	LIN TRNS	NOISE FIG = 3.0 DB
STRUCTURE	0.17	1.63	0.72	161.1	36.60		H = 1.2, D = 9.0 FT
THERMAL CONTROL	0.16	0.24	0.24	34.4	6.88	HEATPIPE	PWR RAD = 3.678 KW
STATION KEEPING	0.23	3.85	1.51	489.3	22.02	RESIST	
ATTITUDE CONTROL	0.24	3.24	1.32	68.6	1.11	RESIST	AM/L = 1145.4 SQ FT
TELEMETRY + COMMAND	0.17	0.85	0.45	70.0	2.00		
PROTOTYPE	-	3.30	1.10				1 PROTOTYPE(S)
INTEG,ASSY + CHECK	1.41	-	1.41				SAT FAILURE RATE =0.10
DESIGN, INTEG + MGMT	-	7.27	2.42				
CENTER SUPPORT	1.22	1.94	1.87				
GRD SUPPORT EQUIP	-	2.82	0.94				
TOTAL/SATELLITE	7.33	9.15	16.48	2827.6	230.08		1 ACTIVE SAT(S)
							0 ORBIT SPARE(S)
							0 GROUND SPARE(S)
							1 SAT(S) IN SYSTEM AT ANY GIVEN TIME

LAUNCH VEHICLE	COSTS (MILLIONS) ACQUISITION	R+D	TOTAL	WEIGHT LIMIT	VOLUME LIMIT		
TOTAL/LAUNCH VEH	18.80	2.20	19.53	2800.0	1170.00	TITAN 3D/B2	1 SATS/LAUNCH
							1 LAUNCH VEHICLES
							LAUNCH VEH FAILURE RATE =0.20

TOTAL NUMBER OF SATELLITES LAUNCHED DURING SYSTEM LIFETIME = 3

Figure 18: Partial Formal Output

number of active satellites, the number of in-orbit spare satellites, and the number of spare satellites in storage on ground in the system at any given time. Also, the total number of satellites launched during the system lifetime and the assumed satellite and launch vehicle failure rates are printed out.

3.12 CHANGES IN INPUT

This section provides definitions of all new input variables added to the modified GD/C program as well as describing modification to existing inputs. A complete listing of all the namelist input variables is available in Reference 7.

NAMELIST/SATT/

ITRFLG(4,4), changed from ITRFLG(4,4,2)
Input array of flags to determine valid combinations of transmitter type and frequency.

NAMELIST/PAR/

WGHTV(2), changed from WGHTV(2,2)
Psophometric weighting factor for FM video

WGHTNG(4), changed from WGHTNG(4,2)
Psophometric weighting factors for audio, facsimile, and digital data. The appropriate value WGHTV is placed in WGHTNG(2) during execution.

PREMV(2), changed from PREMV(2,2) FM pre-emphasis for video.

PREEMP(4), changed from PREEMP(4,2) FM pre-emphasis for each data type. The appropriate value of PREMV is placed in PREEMP(2) during execution.

PEAK, changed from PEAK(2) Peaking factor.

TASOC, changed from TASOC(2) conversion factor to TASO standard.

AINT(4), new
Vector of possible interest (discount) rates to be considered.

FAILLV, new
Launch vehicle failure rate

FAILST, new
Satellite failure rate

FMLC(3), new
Learning curve factors for Class 1, 2, 3 receivers.

ANTLC(3), new
Learning curve factors for Class 1, 2 3 antennas.

NAMELIST/LOSS/

POLDBU(2,2), changed from POLDBU(2)
Uplink polarization loss, in db

POLDBD(3,2), changed from POLDBD(3)
Downlink polarization loss, in db.

POR, new
Scintillation probability

NAMELIST/GRD12/

UCFAC(3,2), changed from UCFAC(3)
Coefficients for determining the unit cost of the facility.

CHC12(2), new
Incremental cost per channel for Class 1, 2 receivers.

NAMELIST/GRD3/

RCVR(2,4), new
Breakpoints for fitting Class 3 receiver cost curves in three pieces.

HRCVR(3,3,4), new
Coefficients and exponents for determining Class 3 receiver cost.

CHC3, new
Incremental cost per channel for Class 3 receivers.

NAMELIST/USRQ/

FCINIT(3,8), new
Initial number of facilities available at system startup for each class and beam.

BETA(3,8), new
Growth curve rate parameter for each class and beam.

IBLD(3,8), new
Growth lifetime for each class and beam.

NOS, new
Number of orbit satellite spares.

NGS, new
Number of ground satellite spares.

C2, new
Relative cost adjustment factor for orbit spare satellites.

C1, new
Relative cost adjustment factor for ground spare satellites.

XINF, new
Inflation rate.

IINT, new
Index vector to select interest (discount) rate from AINT.

IGCPLT(3,8), new
Array of flags to select which growth curves are to be displayed on output. Dimensional as (class) x (beam).

PIACR, new
Satellite integration, assembly and checkout cost as fraction of the cost of various subsystems.

PCSR, new
Center support cost (recurring) as fraction of recurring hardware subsystem recurring costs.

PSPTN, new
Fraction of solar array used in the satellite prototype.

PDIMN, new
Design, integration and management (nonrecurring) costs as fraction of hardware subsystem nonrecurring costs.

PCSN, new
Center support nonrecurring costs as fraction of hardware nonrecurring and Design, Integration and Management costs.

PGSEN, new
Ground support equipment (nonrecurring) costs as fraction of the satellite hardware subsystem unit recurring costs.

The following is a list of variables that were contained in the original GD/C program but were removed from the modified program because they were no longer needed.

```
NAMELIST/SATT/
     EFFLCI
     EFFAM(3,4,3)
     WTRAML(4,3)
     RDTRA1(3,4,3)
     RDTRA2(3,4,3)
     UCTRA1(3,4,3)
     UCTRA2(3,4,3)
     VTRAM1(3,4,3)
     VTRAM2(3,4,3)
     WTRAM1(3,4,3)
     WTRAM2(3,4,3)

NAMELIST/PAR/
     IMD1I
     IMD2I

NAMELIST/GRD12/
     BDAMRC(2,4)
     CRCVAM(3,3,4)

NAMELIST/GRD3/
     HRCVR1(3,2)
     HRCVR2(3,4)
     HRCVR3(3,2)
     RCVR2(2)
     RCVR3(1)
     XLC1(3,3)
     XLC2(3)
     XLC3(3)
     RCVC2
     RCVC3
```

```
NAMELIST/USRQ/
     IMOD1(4)
     IMOD2(4)
```

3.13 OTHER COMPUTER AIDS FOR SYSTEM SYNTHESIS

Another set of programs has been written to aid in the design of a satellite communication system. One of the programs plots, on an off-line plotter, a geographic map of the world or any portion of it. A second program designed to be used with the first, computes the longitude and latitude coordinates of the intersections of satellite antenna beams and the earth. It then plots these "foot-prints" on the map drawn by the first program to show, explicitly, the antenna coverage. A third program was written to plot the earth as seen from an earth-synchronous satellite. These programs are described in more detail in Appendix 7.1. These programs were used to generate the antenna coverage patterns shown in the following chapter.

4. SENSITIVITY ANALYSIS

4.1 2.5 GHz BROADCAST SYSTEM

The modified STAMP was used to synthesize a number of broadcast as well as fixed communications satellite systems in an effort to demonstrate its utility in the determination of lowest cost systems and their sensitivity to variations in technical and user requirements.

The first baseline system considered was defined to be an educational television broadcasting system for the continental United States. The system is composed of a single beam satellite covering the 48 states with a single central ground station transmitting one channel of video to the satellite at 6.2 GHz. The satellite broadcasts the video signal at 2.6 GHz to 20,000 ground receiving stations, presumably located on school roof-tops or other learning centers. The satellite lifetime is 5 years while the system lifetime is 15 years. The launch vehicle used is Titan IIIB/Centaur/Burner II. The failure rates for the launch vehicle and the satellite upon release from the launch vehicle were assumed to the 0.25 and 0.20 respectively. The peak to peak signal to weighted rms noise ratio objective for the direct receivers is 49 db, equivalent to TASO Grade I service for terrestrial Vestigial Side Band (VSB) transmissions. The antenna coverage pattern for this system is shown in Figure 19. The output from the program for this system is shown in Figure 20. As can be seen from

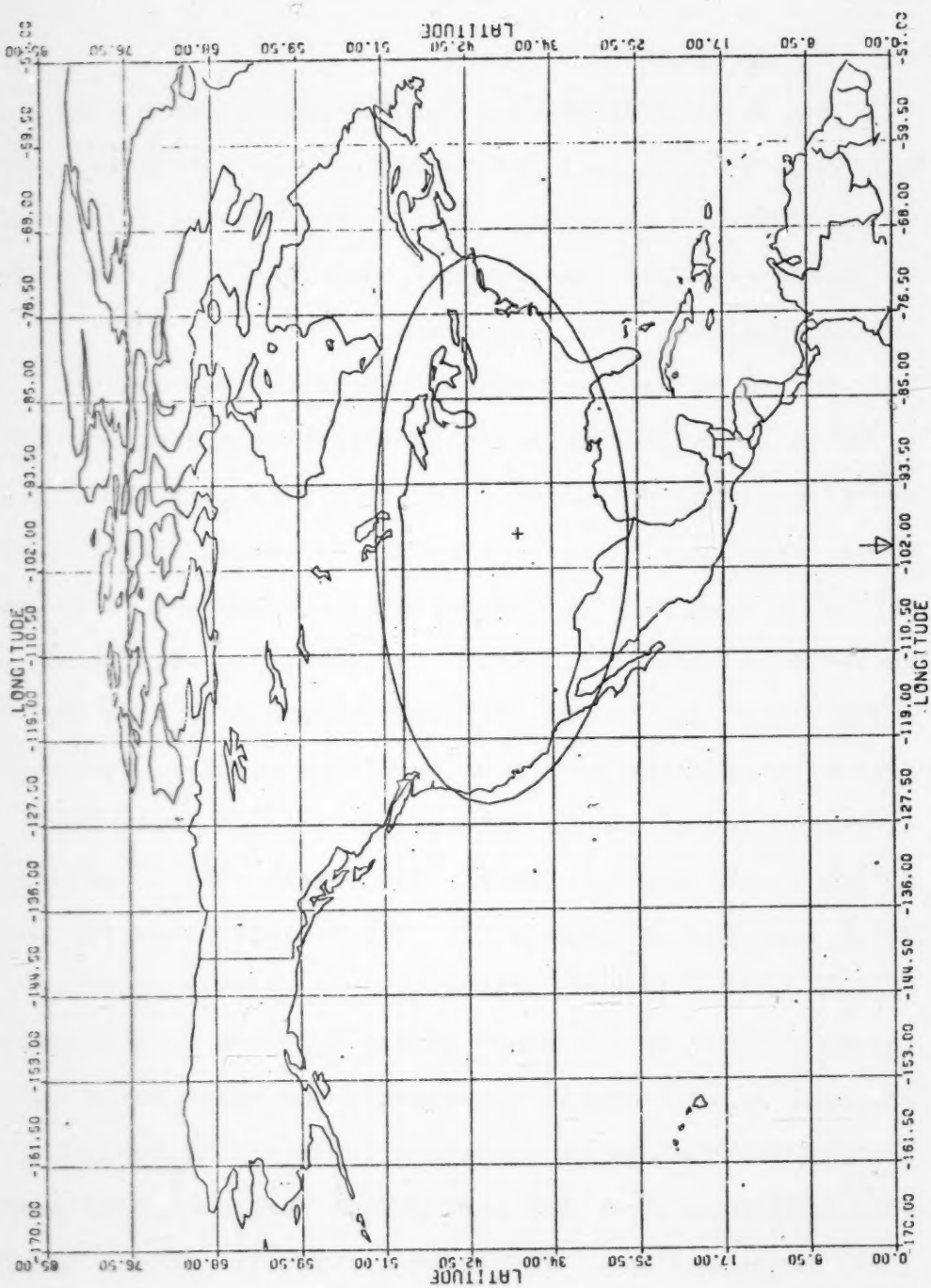

Figure 19: Single Beam CONUS Coverage

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PAGE 1

USER REQUIREMENTS

SATELLITE LONG =-100.0 DEG UPLINK FREQUENCY = 6.20 GHZ
SATELLITE LIFE = 5.0 YEARS DOWNLINK FREQUENCY = 2.60 GHZ
TOTAL SYS LIFE = 15.0 YEARS NUMBER OF BEAMS = 1

USER NO	USER DESCRIPTION	RCVR ENVIR	NUMBER OF STATIONS CLASS 1	CLASS 2	DIRECT
C3	EDUCATIONAL/INSTRUCTIONAL DISTRIBUTION (1 BEAMS) ,	URBAN	1.	0.	20000.

USER NO	TOTAL CAPITAL INVESTMENT (PRESENT VALUE IN MILLIONS) TOTAL	CLASS 1	CLASS 2	DIRECT	SPACE SEG	TLM/CMD
C3	115.461	0.171	0.0	29.877	84.870	0.543

USER NO	AVERAGE ANNUAL OPERATING COST (IN MILLIONS) TOTAL	CLASS 1	CLASS 2	DIRECT	TLM/CMD
C3	2.254	0.085	0.0	2.036	0.134

USER NO	PRESENT VALUE OF ANNUAL OPERATING COST (IN MILLIONS) TOTAL	CLASS 1	CLASS 2	DIRECT	TLM/CMD
C3	21.495	0.806	0.0	19.416	1.273

USER NO	DISCOUNT RATE (PER CENT)	INFLATION RATE (PER CENT)
C3	10.0	3.5

Figure 20: Sample Program Output

USER NO	SERVICE TYPE	BASE-BAND (MHZ)	VEST-BAND (MHZ)	NO AUDIO CHANNELS /VIDEO	VIDEO DATA MODULATION UPLINK	DNLINK	MOD INDEX UPLINK	DNLINK	RF BANDWIDTH UPLINK (MHZ)	DNLINK (MHZ)
03	COLOR	4.200	0.0	2	FM	FM	3.00	3.00	33.60	33.60

Figure 20: Sample Program Output
(continued)

BEAM NO	NO OF FAC	NO OF CHANS XMTD AUDIO	VIDEO	FAX	DIGIT	EIRP (DBW) AUDIO	VIDEO	FAX	DIGIT	NO OF CHANS RCVD AUDIO	VIDEO	FAX	DIGIT	G/T (DB/K)	SIGNAL/NOISE (DB) AUDIO	VIDEO	FAX	DIGIT
1	1.	0	1	0	0	0.0	82.6	0.0	0.0	0	1	0	0	4.5	0.0	56.0	0.0	0.0

BEAM NO	NUMBER OF RECEIVERS	NO OF CHANS RCVD AUDIO	VIDEO	FAX	DIGIT	G/T (DB/K)	SIGNAL/NOISE (DB) AUDIO	VIDEO	FAX	DIGIT	RCVR ANTENNA NOISE DISCRIMINATIONS CLASS 1 SKY	ENVIR	EARTH	CLASS 2 SKY	ENVIR	EARTH	DIRECT SKY	ENVIR	EARTH
1	20000.	0	1	0	0	2.77	0.0	49.0	0.0	0.0	0.867	0.009	0.012	0.0	0.0	0.0	0.763	0.017	0.095

BEAM NO	NO OF CHANS RCVD AUDIO	VIDEO	FAX	DIGIT	G/T (DB/K)	NO OF CHANS XMTD AUDIO	VIDEO	FAX	DIGIT	EIRP (DBW) AUDIO	VIDEO	FAX	DIGIT
1	0	1	0	0	10.60	0	1	0	0	0.0	60.0	0.0	0.0

BEAM NO	ANTENNA DIMENSIONS (FT)		BEAM CENTER LAT (DEG)	LONG (DEG)	UPLINK GAIN (DB)	BEAMWIDTHS (DEG)	(DEG)	PATTERN AXES (MI)	(MI)	DOWNLINK GAIN (DB)	BEAMWIDTHS (DEG)	(DEG)	PATTERN AXES (MI)	(MI)
1	3.9	8.8	37.4	-98.5	38.7	2.85	1.26	1651.	510.	31.1	6.80	3.00	4268.	1227.

Figure 20: Sample Program Output
(continued)

BEAM NO	DOWNLINK NOISES (DEG K)																	UPLINK NOISES		
	SKY	ENVIR	EARTH	INTERMODULATION NOISE AUDIO	VIDEO	FAX	DIGIT	UPLINK CONTRIBUTION AUDIO	VIDEO	FAX	DIGIT	CLASS 1 RCVR	RCVR CKT	CLASS 2 RCVR	RCVR CKT	DIRECT RCVR	RCVR CKT	EARTH	RCVR	RCVR CKT
1	57.8	93.1	290.0	0.	0.	0.	0.	0.0	706.5	0.0	0.0	6994.5	19.4	0.0	19.4	523.4	59.6	290.0	290.0	59.6

BEAM NO	UPLINK LOSSES (DB)							CLASS 1 STATION				CLASS 2 STATION			
	FREE-SPACE	ATMOSPHRIC	RAIN	SCINT	LOCATION	SAT RCVR CKT	SAT RCVR POINT	XMIT CKT	XMIT POINT	POLARIZATION	ELEV (DEG)	XMIT CKT	XMIT POINT	POLARIZATION	ELEV (DEG)
1	-200.6	-2.6	-0.3	0.0	-10.8	-1.0	-0.1	-3.0	-0.1	0.0	5.0	-3.0	-0.1	0.0	5.0

BEAM NO	DOWNLINK LOSSES (DB)							CLASS 1 STATION				CLASS 2 STATION				DIRECT RECEIVER			
	FREE-SPACE	ATMOSPHRIC	RAIN	SCINT	LOCATION	SAT XMTR CKT	SAT XMTR POINT	RCVR CKT	RCVR POINT	POLARIZATION	ELEV (DEG)	RCVR CKT	RCVR POINT	POLARIZATION	ELEV (DEG)	RCVR CKT	RCVR POINT	POLARIZATION	ELEV (DEG)
1	-193.0	-1.0	-0.0	0.0	-1.9	-1.2	-0.1	-0.3	-0.1	0.0	5.0	-0.3	-0.1	0.0	5.0	-1.0	-2.0	-3.0	5.0

Figure 20: Sample Program Output
(continued)

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GROUND STATIONS - BEAM 1 (THOUSANDS)

CLASS 1 FACILITIES	ACQUISITION	INSTALL	OPER/YEAR	MAINT/YEAR	TOTAL	
FACILITY	0.0	-	-	0.0	0.0	
TERMINAL EQUIP-VIDEO	0.0	0.0	0.0	0.0	0.0	NO. CHANS = 2
TRANSMITTERS-VIDEO	81.13	12.17	70.69	8.11	1275.28	POWER = 3.312 KW
ANTENNA + MUX	56.70	0.0	-	5.67	141.75	DIA = 22.98, G =50.43 43.00
RECEIVERS	0.61	0.09	0.03	0.06	2.07	NOISE FIG =14.00 TEMP =6994.47
STANDBY POWER	0.0	0.0	-	0.0	0.0	
TEST EQUIPMENT	0.0	-	-	-	0.0	
PERSONNEL	-	-	0.0	-	0.0	
DESIGN, INTEG + MGMT	-	20.77	-	-	20.77	
TOTAL/FACILITY	138.44	33.03	70.72	13.84	1439.87	NO FAC/BEAM = 1.

DIRECT STATIONS	ACQUISITION	INSTALL	MAINT/YR	TOTAL	(DOLLARS)	
ANTENNA	272.69	103.31	27.27	785.02		DIA = 5.7, GAIN= 30.8 DB
RECEIVER	745.24	372.62	74.52	2235.73		NF = 4.5 DB TEMP = 523.43
						NO. CHANS = 1
	1017.93	475.93	101.79	3020.75		NO FAC/BEAM = 20000.

Figure 20: Sample Program Output
(continued)

SATELLITE SUBSYSTEMS	COSTS (MILLIONS) ACQUISITION	R+D	TOTAL	WEIGHT (LBS.)	VOLUME (CU FT)	TYPE	DESCRIPTIVE PARAMETERS
POWER SUBSYSTEM							
PRIME POWER	0.94	0.19	1.01	368.4	61.52	SOLAR	POWER = 2.538 KW
SECONDARY POWER	0.01	0.10	0.04	293.6	2.44	NI-CAD	CAPACITY = 5.442 KW-H
CONDITIONING	0.07	0.15	0.12	156.0	2.10		
DISTRIBUTION	0.16	0.24	0.24	36.2	3.56		
ANTENNA	0.01	0.06	0.03	31.7	209.06	RIGID	DIAM = 8.82, 1 BEAMS
TRANSMITTER	0.14	0.83	0.42	61.9	1.46	TWT	1. TRANSMITTERS
MULTIPLEXER	0.01	0.01	0.01	11.5	0.38	WAVEGUID	
RECEIVERS	0.10	0.20	0.17	35.0	1.17	LIN TRNS	NOISE FIG = 3.0 DB
STRUCTURE	0.16	1.57	0.69	147.9	33.40		H = 0.7, D = 9.0 FT
THERMAL CONTROL	0.11	0.17	0.17	15.7	3.13	HEATPIPE	PWR RAD = 1.769 KW
STATION KEEPING	0.17	3.55	1.36	270.8	12.19	RESIST	
ATTITUDE CONTROL	0.23	3.23	1.31	66.4	1.09	RESIST	AM/L = 852.2 SQ FT
TELEMETRY + COMMAND	0.17	0.85	0.45	70.0	2.00		
PROTOTYPE	-	1.49	0.50				1 PROTOTYPE(S)
INTEG,ASSY + CHECK	0.69	-	0.69				SAT FAILURE RATE =0.20
DESIGN, INTEG + MGMT	-	6.69	2.23				
CENTER SUPPORT	0.59	1.78	1.19				
GRD SUPPORT EQUIP	-	1.37	0.46				
TOTAL/SATELLITE	3.57	7.49	11.06	1565.0	333.49		1 ACTIVE SAT(S) 0 ORBIT SPARE(S) 0 GROUND SPARE(S) 1 SAT(S) IN SYSTEM AT ANY GIVEN TIME

LAUNCH VEHICLE	COSTS (MILLIONS) ACQUISITION	R+D	TOTAL	WEIGHT LIMIT	VOLUME LIMIT		
TOTAL/LAUNCH VEH	14.40	5.00	16.07	1800.0	1170.00	TIT 3B/CEN/2	1 SATS/LAUNCH 1 LAUNCH VEHICLES LAUNCH VEH FAILURE RATE =0.25

TOTAL NUMBER OF SATELLITES LAUNCHED DURING SYSTEM LIFETIME = 3

Figure 20: Sample Program Output
(continued)

SATELLITE COMMUNICATIONS SUBSYSTEMS

BEAM NO. 1	UNIT ACQ	TOTAL ACQ	TOTAL WEIGHT	TOTAL VOLUME	POWER (WATTS)	EFFIC-IENCY.	UNIT LIFE	MOD	NO.XMTR BLOCKS	NO XMTRS /BLOCK	
TRANSMITTER- TWT											
-VIDEO	C.06	0.14	61.9	1.46	1019.	60.9	2.	FM	1	3.	
MULTIPLEX-WAVEGUID		0.01	11.5	0.38							LOSS=-0.2 DB
RECEIVER-LIN TRNS		0.10	35.0	1.17	10.		2.				NF = 3.0 DB

Figure 20: Sample Program Output
(continued)

page 1 of the output, the present value of the capital investments is $115.461 million. This value accounts for all the initial costs incurred in the system including the costs of the satellites launched 5 years and 10 years hence inflated and discounted to present value with inflation and discount rates of 3.5% and 10% respectively. Since the present value of the annual expense is $21.495 million, the total value of this system is $136.956 million.

The system was synthesized twice again with the same inputs and constraints except that the number of channels was first changed to two and then to four. The effect of these changes on the system costs is shown in Figure 21. The increase in system cost is very linear with the number of channels as is the ground segment cost. The space segment cost is very nearly constant, increasing only slightly with the number of channels. This is due to the fact that the size of the satellite is constrained by the launch vehicle chosen. As the number of channels increases, the power available for transmission from the satellite, which remains relatively constant, must be divided among all the channels thus lowering the EIRP/channel. To maintain the required signal quality at the ground receiving stations the G/T of these stations must increase. Figure 22 shows the EIRP/channel and the G/T of the ground receiving stations indicating that they are indeed complementary functions. Since the size of the satellite remains basically constant due to the weight constraint imposed by the launch vehicle, the

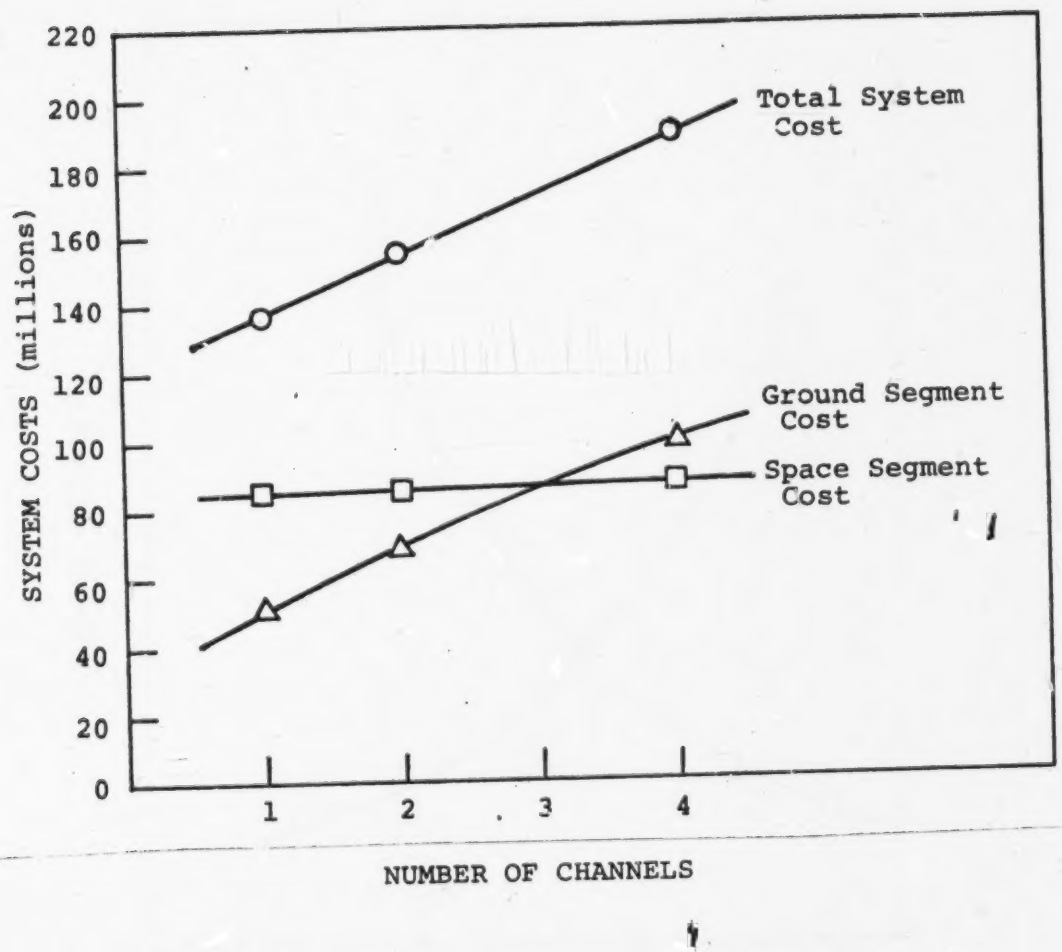

Figure 21: System Cost versus Video Channels Broadcast

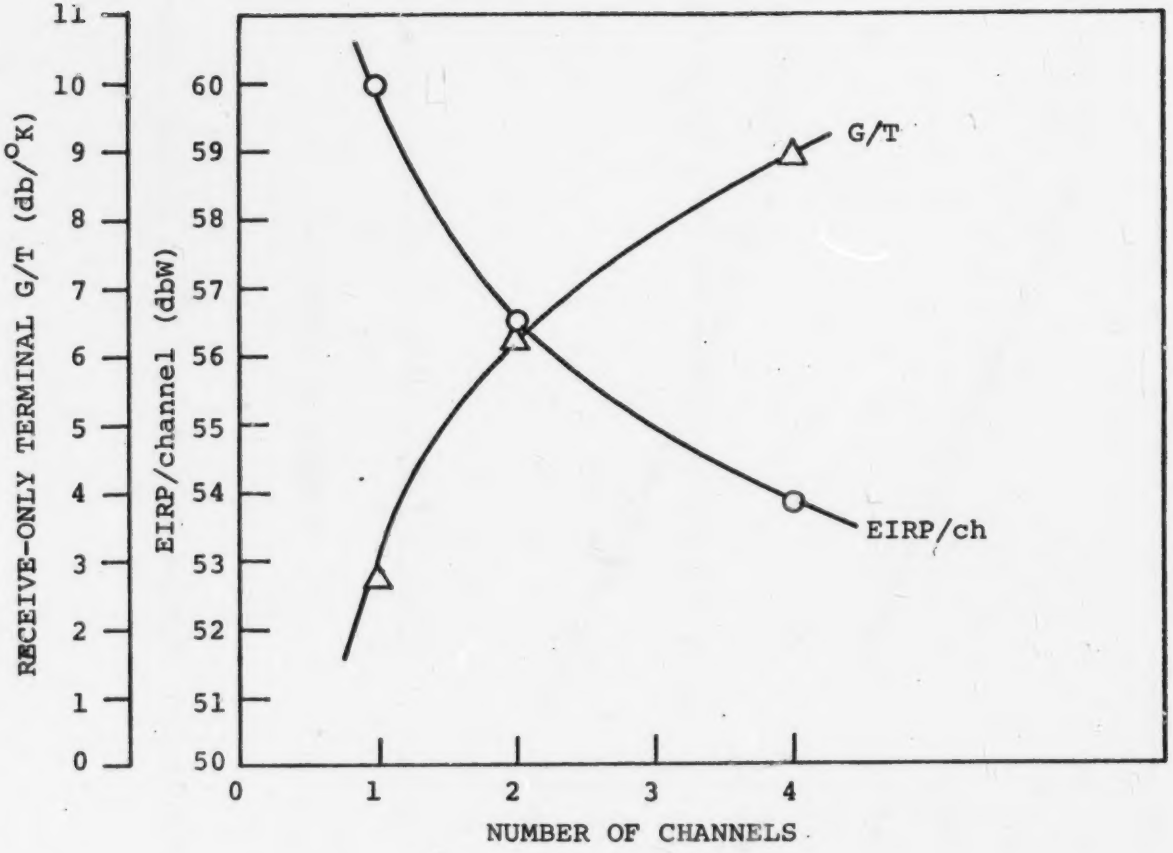

Figure 22: G/T, EIRP versus Video Channels Broadcast

cost of the space segment remains constant. The increase in total system cost is then due to the increase in ground station costs.

This single beam, four channel broadcast system for continental U.S. was rerun twice again, this time with 10,000 and then 5,000 ground receiving stations. The effect on the system costs is shown in Figure 24. Again, the space segment cost is fairly constant because of the launch vehicle constraint and the increase in system cost is due to the increase in the ground segment cost. Figure 23 shows the satellite EIRP/channel and the ground receiving station G/T trade-off. In this case the EIRP/channel is constant since the number of channels is constant. Therefore, the earth station G/T is relatively constant and the increased cost is due solely to the increased number of ground stations.

It is interesting to note what happens to this system when the satellite size constraint is relaxed by choosing a larger launch vehicle, namely Titan IIID/Burner II. The dotted lines in Figure 23 and 24 show the effect this has on the system costs, EIRP/channel and G/T. Figure 24 shows that the ground segment cost increase is not as rapid with the number of ground stations and that the space segment cost increases more. This is due to the fact that the satellite in the 5000 receiver system is considerably smaller than the maximum allowed by the larger launch vehicle.

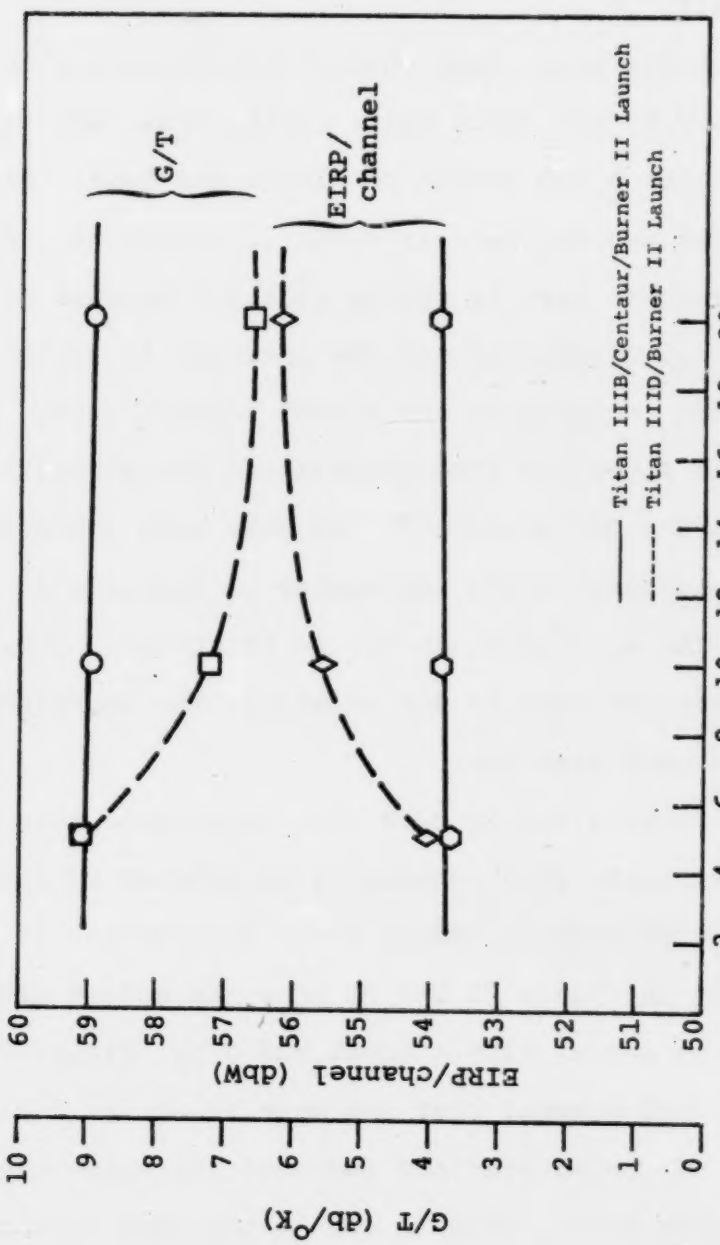
G/T
EIRP/
channel
Titan IIIB/Centaur/Burner II Launch
Titan IIID/Burner II Launch
NUMBER OF CLASS III STATIONS (X 1000)
2 4 6 8 10 12 14 16 18 20
EIRP/channel (dbW)
60 59 58 57 56 55 54 53 52 51 50
G/T (db/°K)
10 9 8 7 6 5 4 3 2 1 0

Figure 23: G/T, EIRP Ground Station Population Dependence

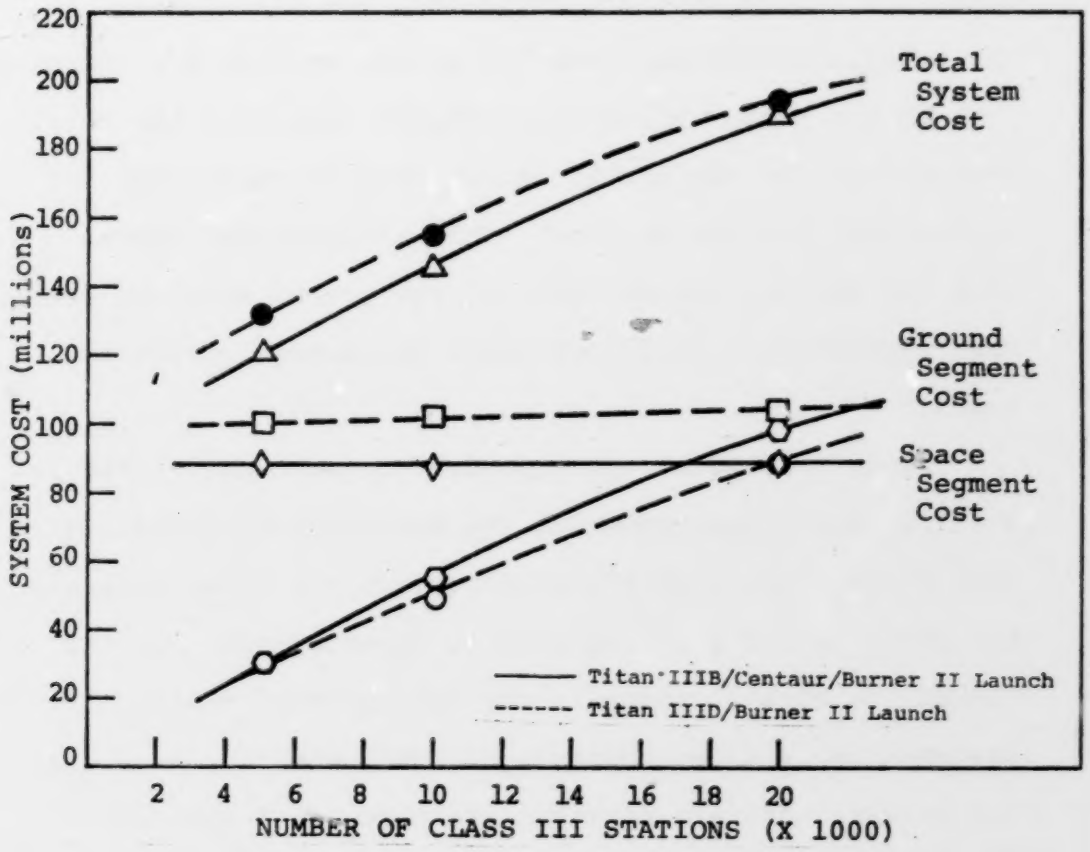

Figure 24: System Cost Ground Station Population Dependence

This gives the satellite room to "grow" in future generations with the number of ground stations. The dotted lines in Figure 23 display this growth more explicitly. As the number of ground stations increases, the EIRP/channel at the satellite increases and the ground station G/T decreases.

As the number of ground stations increases the total system cost for the larger launch vehicle approaches the system cost for the smaller. This is important since, with the smaller launch vehicle, the ground stations are more expensive, a fact that could discourage potential users.

Next, the system was expanded to two beams. This is still a single beam covering the continental United States with 20,000 receiving stations receiving 4 video channels but now there is a second beam to cover Alaska. On the ground, in Alaska, there is one transmitting station transmitting 4 video channels and 400 receiving stations. The antenna coverage patterns are shown in Figure 25. The smaller launch vehicle, namely Titan IIIB/Centaur/ Burner II, was chosen first, since it yielded a least cost system for the single beam system. The sub-satellite longitude was shifted from 100° west to 120° west to improve the noise conditions in the Alaskan beam. The cost changes for a 4 channel video broadcast system are summarized as follows:

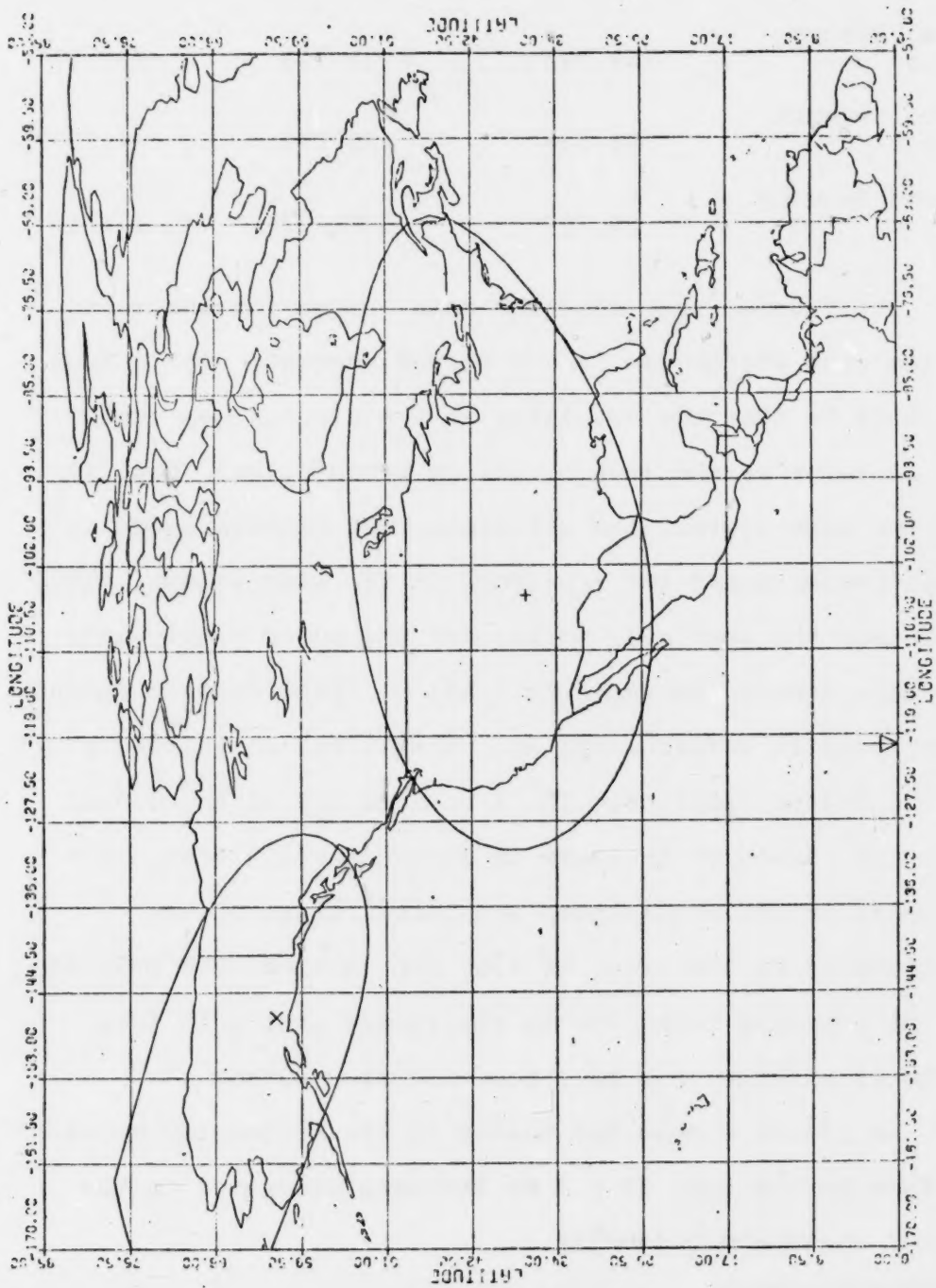

Figure 25: Two Beam Alaska and CONUS Coverage

	1 beam system (continental U.S.)	2 beam system (continental U.S. and Alaska)	cost change
Total System Cost	189.883	215.743	25.860
Space Segment Cost	88.339	93.077	4.738
Ground Segment Cost	99.729	120.859	21.130

The figures show that the main source for the total system cost change was in the ground segment. The reason for this is that the satellite in the single beam system was as large as the launch vehicle would allow. Now, in the two beam system, the satellite must contain twice as many transmitters* and receivers in the same volume. This decreases the available volume for the power supply and, thereby, lowers its capacity. All of these changes demand a decrease in EIRP/channel and, therefore, an increased G/T at the ground stations. The increased G/T at the ground stations causes an increase in ground station cost. The increase in the acquisition and installation of the stations is on the order of $550 per station, the majority of the increase being due to the change from a 10 foot diameter antenna to a 12.3 foot diameter antenna.

In adding a beam for Alaska to the system the mainland suffers in the form of a 2 db increase necessary in the ground station G/T (db/^{o}K).

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*The transmitters are assumed to be channelized throughout this study.

In order to try to decrease the cost of the receivers incurred by the G/T increase, a larger launch vehicle, namely the Titan IIID/Burner II, was chosen and the two beam system was run again. The larger vehicle succeeded in not only reducing the ground segment cost but it also reduced the total system cost by $9.5 million. The cost comparison is given below.

	small LV (Titan IIIB/ Centaur/ Burner II)	large LV (Titan IIID/ Burner II)	cost change
Total System Cost	215.743	206.164	-9.579
Space Segment Cost	93.077	112.214	+19.137
Ground Segment Cost	120.859	92.135	-28.724

The larger launch vehicle allows the EIRP/channel to increase from 51.4 dbw to 55.2 dbw on the mainland and from 50.1 dbw to 53.9 dbw in the Alaskan beam. This allows the G/T of the ground receiving terminals to drop from 11.01 db/^{o}K to 7.22 db/^{o}K and the cost to drop by $840 per terminal below the small ground terminal cost in the single beam system. The change in the total system cost incurred by adding Alaska, when the larger launch vehicle is used, is reduced from $25.860 million to $16.281 million.

The system was then expanded to include Hawaii. This involved adding a third beam to cover the islands, which contain one more transmitting station and 250 more receiving stations. The antenna coverage is shown in Figure 26.

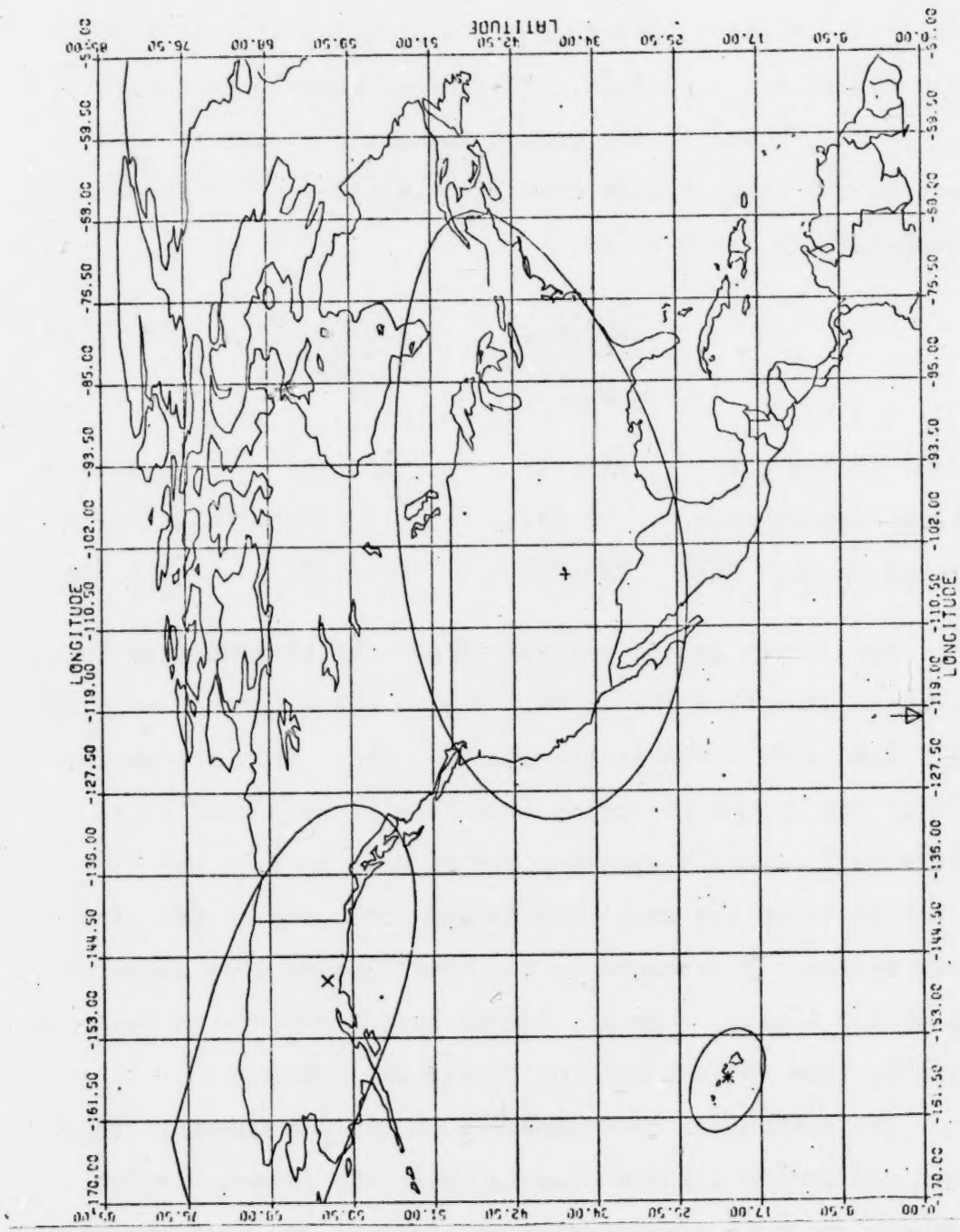

Figure 26: Three Beam Hawaii, Alaska and CONUS Coverage

Titan IIID/Burner II vehicle was chosen for this run. Since the satellite was at its maximum allowable size on the two beam run, then adding another beam will reduce the EIRP/channel and cause an increase in ground station G/T. The cost comparison (in millions of dollars) is given below:

	2 beam system	3 beam system	cost change
Total System Cost	206.164	216.376	10.212
Space Segment Cost	112.214	116.757	4.543
Ground Segment Cost	92.135	97.803	5.668

The EIRP/channel in the mainland beam drops by .8 db/^{o}K. It is interesting to note, in this case, that the G/T computed for the Hawaiian ground stations is slightly higher than that of the Alaskan or mainland stations. In this case, in both Alaska and the mainland, the lowest ground station elevation angle is 5^{o}. It is for this low elevation angle that the communication link is designed. Since the lowest elevation of the Hawaiian beam is 36.6^{o} the G/T will be slightly higher due to reduced atmospheric losses and noise.

Again the mainland suffers a "penalty" for the addition of the Hawaiian beam. However, in this case the "penalty" incurred in terms of ground station acquisition and installation cost is only on the order of $115 per station.

The three beam system was rerun with Titan IIIB/Centaur/ Burner II launch vehicle for the purposes of comparison. The comparison of the 1, 2 and 3 beam systems is shown in Figure 27. The solid lines indicate the system costs when using the smaller launch vehicle while the dotted lines indicate the system costs when using an optimal launch vehicle, that is, using the large vehicle (Titan IIID/ Burner II) for the two and three beam systems.

The three beam system was run another time with the subsatellite longitude moved back from 120° west to 100° west to observe any system changes. The system, however, remained relatively stable indicating that changing the satellite position between 100° west and 120° west will have only a minor effect on system cost at 2.5 GHz.

A new system was defined with the same 3 beam coverage pattern but this time 2 video channels were used instead of 4. The number of ground receiving stations remained the same with 20,000 in the continental United States, 400 in Alaska and 250 in Hawaii. The single beam coverage of the mainland was divided into two beams and the system was rerun. These two beams were then divided into four beams and it was run again. The coverage patterns for the last two cases are shown in Figure 28 and 29. The effect on the system costs is shown in Figure 30. The dotted lines show the same system run with Titan IIID/Burner II vehicle and the solid lines with Titan IIIB/Centaur/Burner II. As can

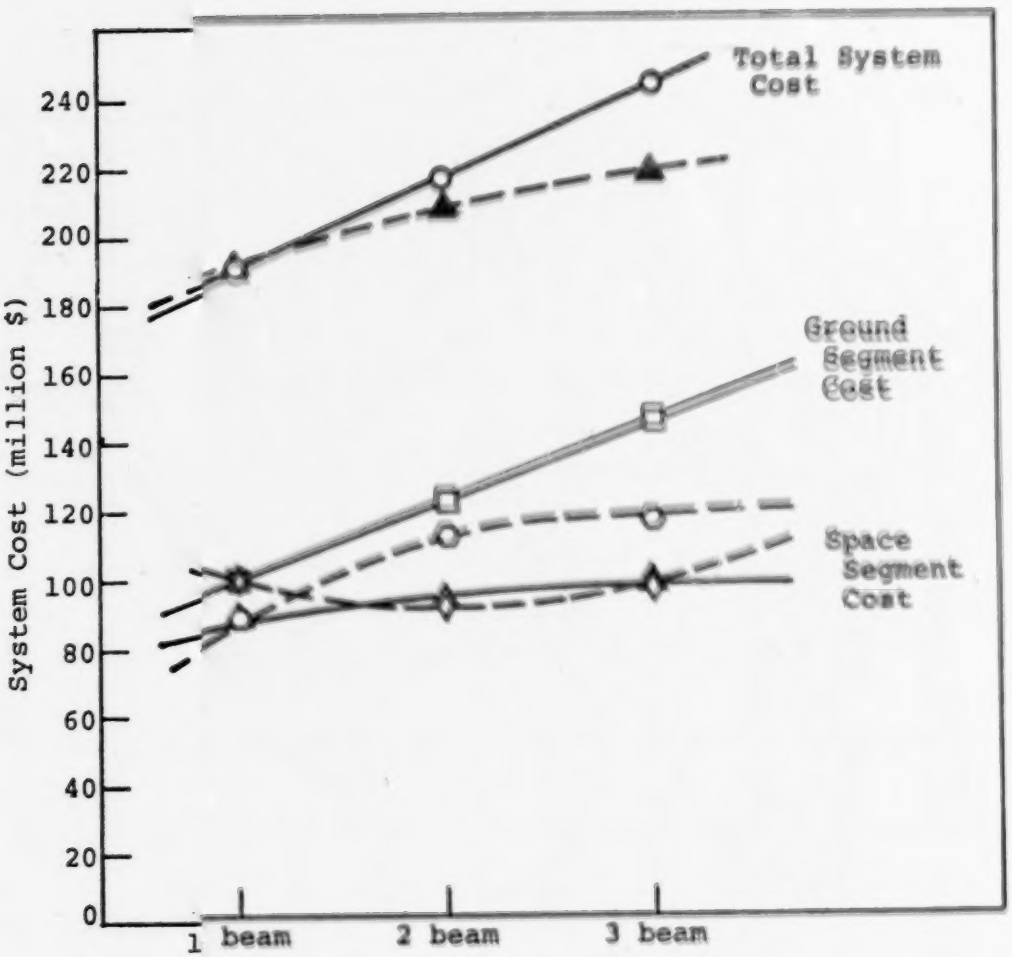

Figure 27: System Cost Beam Number Dependence

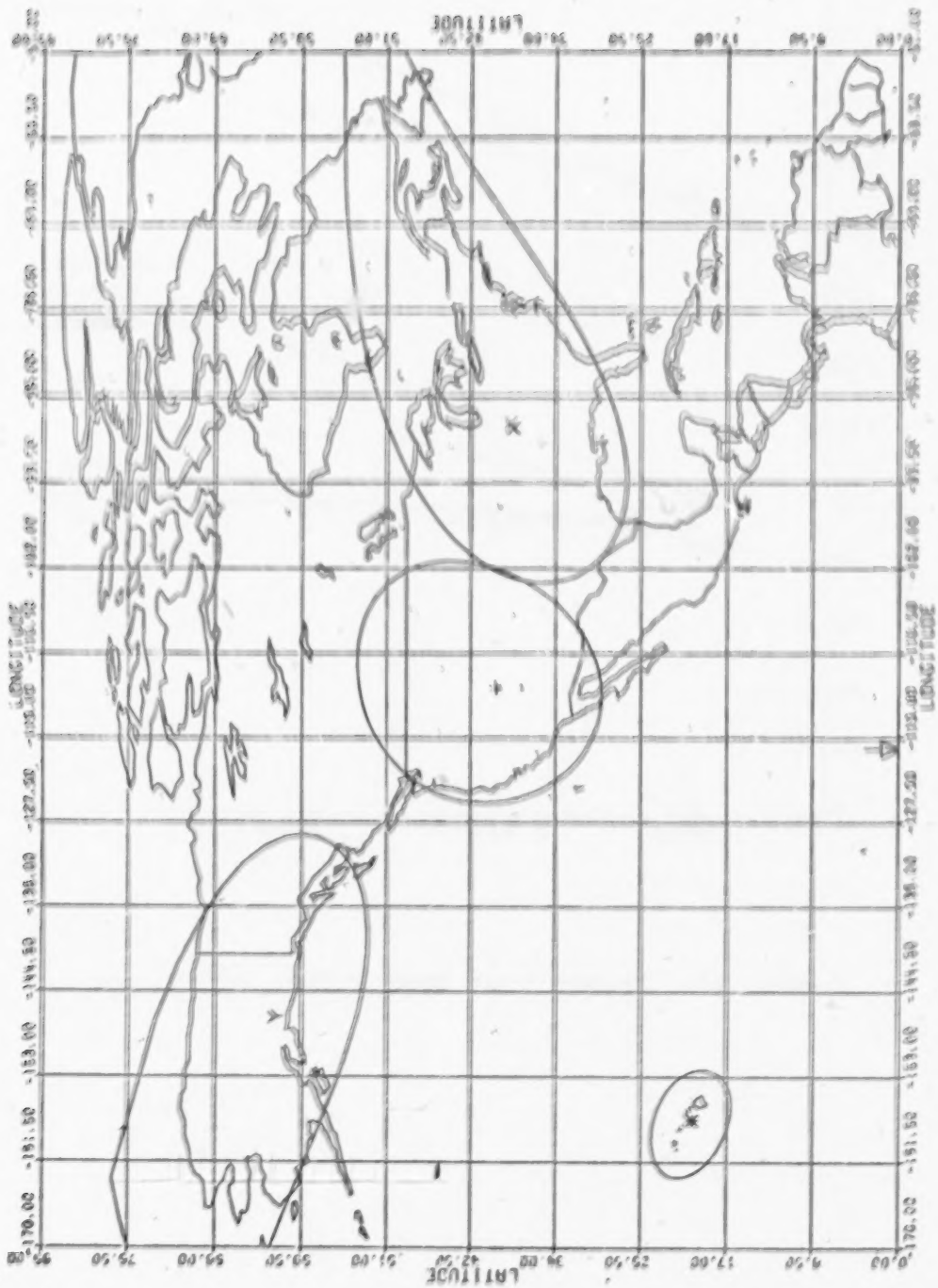

Figure 28: Four Beam Hawaii, Alaska and CONUS Coverage

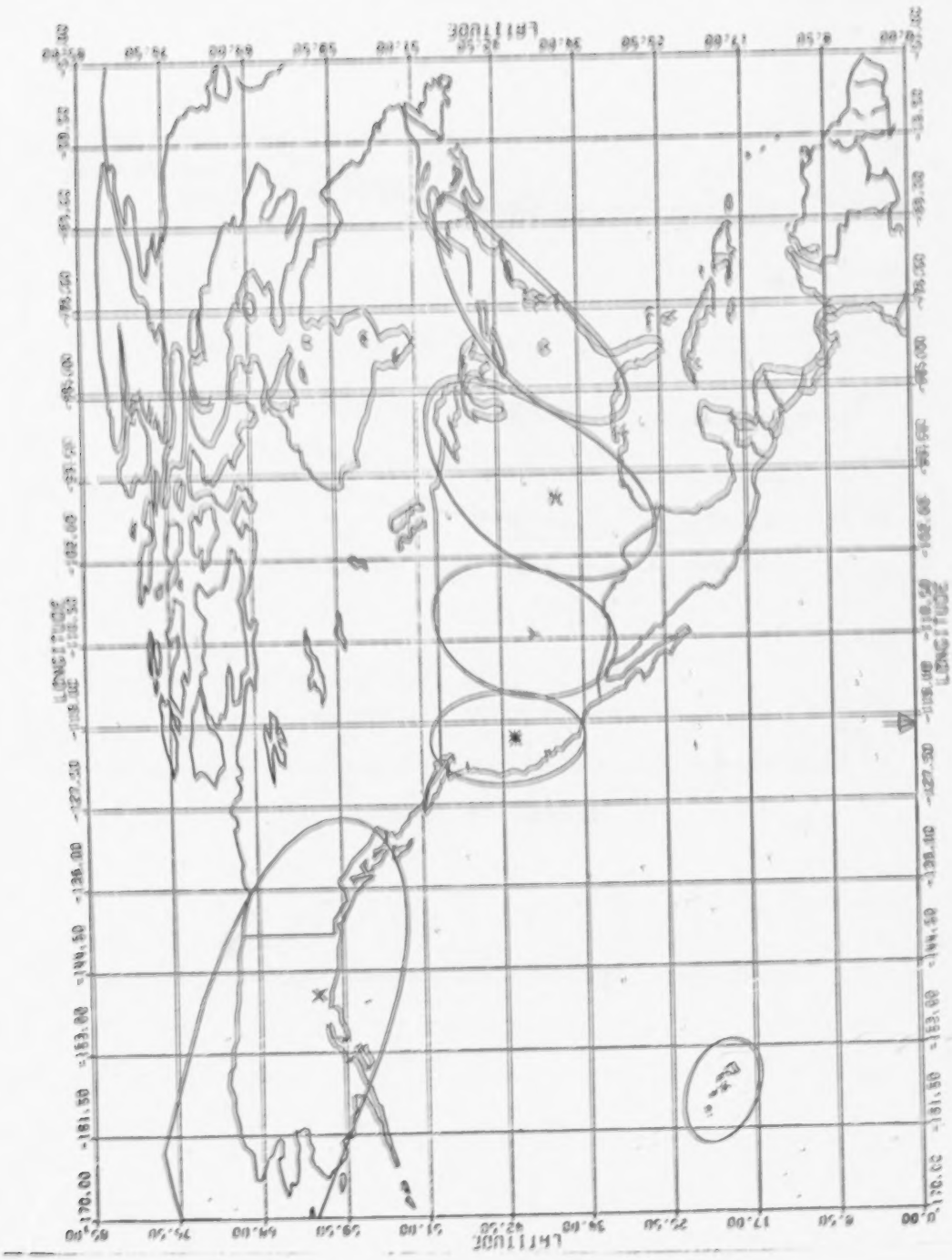

Figure 29: Six Beam Hawaii, Alaska and CONUS Coverage

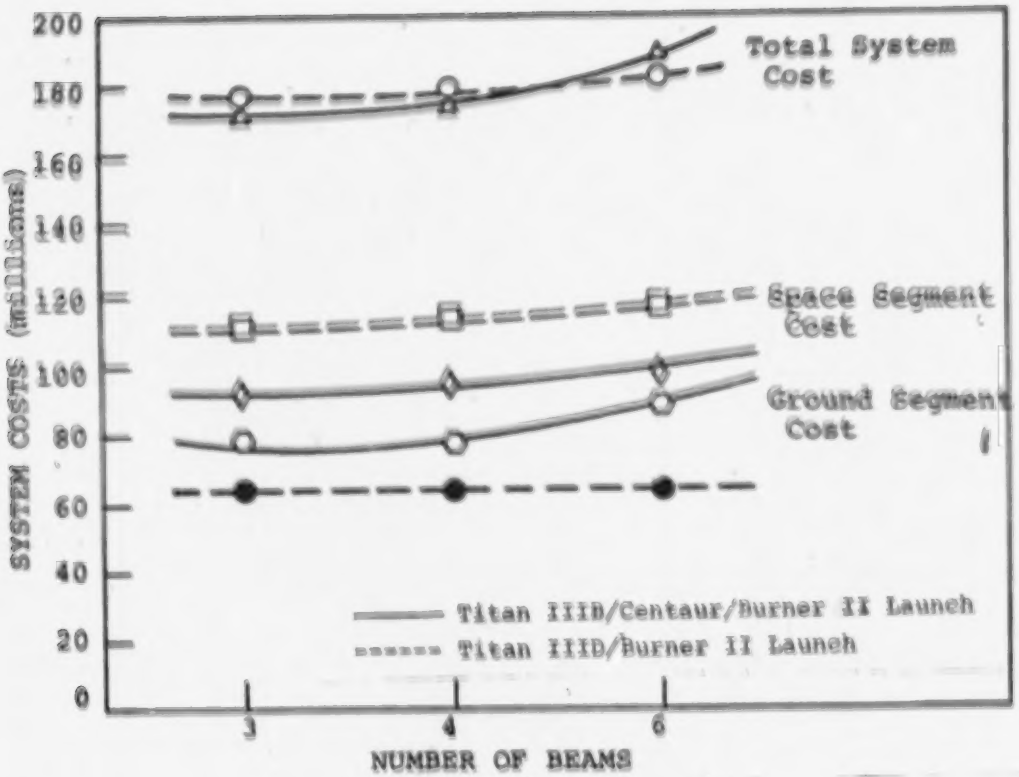

Figure 30: System Cost versus Coverage

be seen, the smaller launch vehicle, namely Titan IIIB/ Centaur/Burner II, provides the least cost system for the 3 beam and 4 beam systems. When six beams are required, however, the satellite performance becomes limited by the size. The sensitivity (G/T) of the ground station must increase and, therefore, so does cost. It can also be seen that when using the larger launch vehicle (Titan IIID/ Burner II), the ground segment costs remain virtually constant while the space segment costs increase slightly. Figure 31 shows the effect of changing the mainland number of beams on the ground receiver G/T and satellite EIRP/ channel of the Hawaiian beam. The solid lines are the curves obtained from using the smaller launch vehicle while dotted lines are obtained from using the larger. When the larger launch vehicle is chosen the EIRP/channel increases allowing the ground station G/T to decrease, as expected. However, when the smaller launch vehicle is specified, the EIRP/channel decreases due to the size constraints and the fact that there are more transmitters and receivers in the satellite.

4.2 2.5 GHz LIMITED TWO-WAY INTERACTIVE SYSTEMS

Using the 3 beam, 2 channel, 20,000 ground station system covering Alaska, Hawaii and the mainland, as a base, a new system using a Titan IIID/Burner II launch was devised to provide voice equivalent interactive capabilities

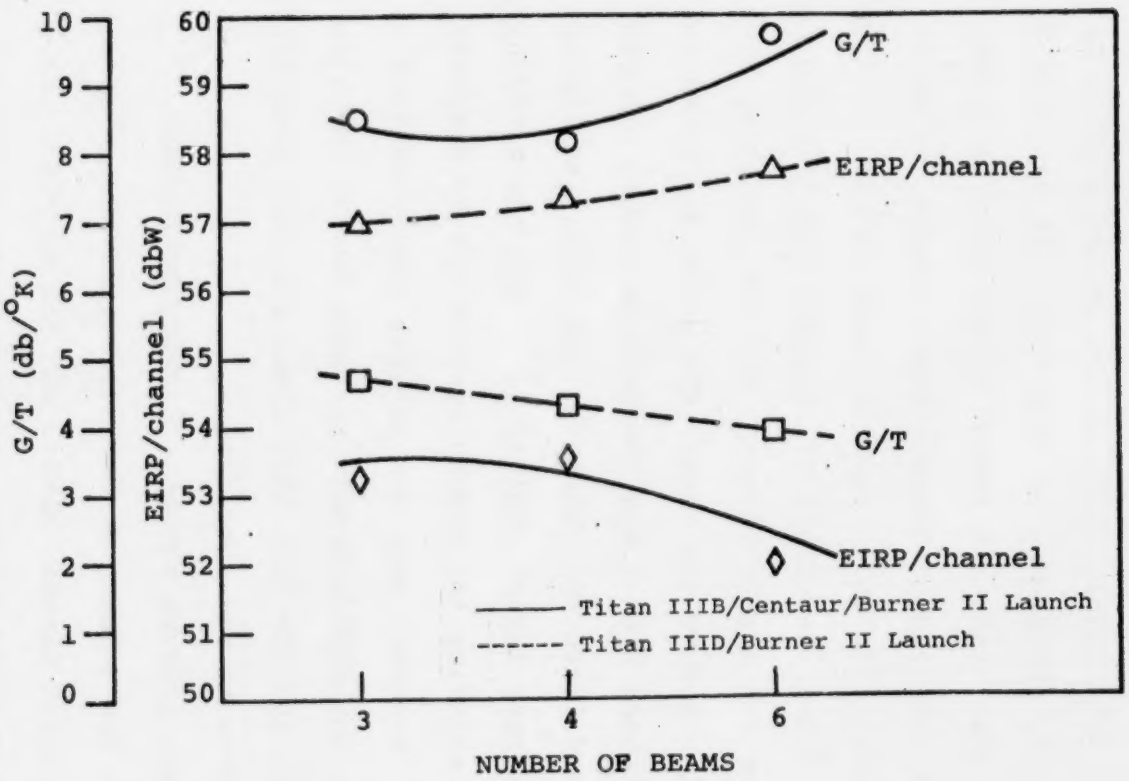

Figure 31: EIRP/Channel and G/T in Hawaiian Beam

in 2.5 GHz DAMA* allocation between some of the remote learning centers and the main ground station in each beam. The single video origination ground facility in the mainland beam, in addition to transmitting the two video channels, now also transmits and receives 200 audio or equivalent bandwidth data channels. Each of the central facilities in the Alaskan and Hawaiian beams now transmits and receives 40 audio channels plus the two video channels. Of the 20,000 ground receiving stations on the mainland, 1000 were given the capability to transmit a single audio channel in order to communicate with the central video origination station. The other 19,000 ground stations remain as receive only stations receiving the two video channels. One hundred of the 400 Alaskan ground stations were given the interactive capability as were 80 of the 150 Hawaiian stations. The satellite was given the capability to receive and retransmit 200 audio channels in the mainland beam and 40 audio channels each in the Hawaiian and Alaskan beams. The cost comparison between this interactive system and the receive only system are given below:

	Receive Only	Interactive	Cost Change
Total System	177.851	265.698	87.847
Space Segment	111.080	113.379	2.299
Ground Segment	64.955	150.503	85.548

*Demand Assigned Multiple Access.

Clearly, the majority of the cost increase is due to the ground segment cost increase. The satellite is constrained by the Titan IIID/Burner II launch vehicle, which is the same in both cases.

The acquisition and installation costs (in million $) of each type of ground stations are given below:

	Costs		Number of Stations	
	Receive Only System	Interactive System	Receive Only System	Interactive System
Class 1 (Transmit/ Receive)	0.539	0.903	3	3
Class 2 (Narrowband Transmit/Wideband Receive)	-	21.870	0	1,180
Direct (Wideband Receive Only)	38.389	37.606	20,650	19,470

The direct terminals have video receive-only capability, the Class 2 stations are very much like direct terminals but with added narrowband interactive capability and the Class 1 stations are the master origination stations with full video/audio transmit/receive capability. The cost of the direct station segment decreases when the interactive capability is added but this is due only to the fact that the number of direct stations decreased by 1180 stations. The actual cost per station increases by $75. This cost increase for the direct stations is necessitated by the

the slightly reduced satellite EIRP due to increased onboard equipment requirements constrained to the same size. The Class 2 costs average to $18,500 per station. The Class 2 stations have a different cost for each beam since the transmitter powers differ for each beam. The Class 2 receivers and antennas are identical for all Class 2 stations. The difference in cost between the $1930 direct stations and the $18,500 Class 2 stations is due in a large part to the $10,100 average transmitter cost and to the $6000 cost of larger circularly polarized antennas used in the Class 2 stations for 2.5 GHz operation. The remainder of the cost difference can be traced to the manufacturing learning curve. The direct stations benefit from the cost reduction incurred by mass production of 19,470 identical stations. The cost reduction for the direct class stations is by a factor of 4.39. Meanwhile, the Class 2 stations benefit from the cost reduction of mass producing only 1180 identical antenna-receiver combinations, a cost reduction by a factor of 2.73. Also, the Class 2 transmitters do not benefit much from a cost reduction due to the fact that they are designed individually for each beam.

In an educational telecommunication system like the above, the areas which would need the interactive capability most would be the remote regions of the Rocky Mountains, Alaska and the Appalachias. Because of the poorer educational and telecommunications facilities

in these areas, an interactive system could provide a greater increase in the educational quality through access to innovative services than in areas where good facilities already exist. This would tend to equalize quality of education in these regions to a level with the rest of the nation. If the Class 2 stations are contained within these regions, then the previous three beam system is somewhat wasteful of signal power. The narrowband channels are repeated over the entire continental United States while they are being used in only small regions of the country. With this in mind, a new system was developed using a six beam satellite. The coverage pattern is that shown in Figure 29. The continental United States was divided into four beams. Each of these beams contains a single master ground station. The interactive capability remained the same in Alaskan and Hawaiian beams. The number of direct class stations remains at 300 to 170 in Alaska and Hawaii, respectively. The four beams covering the mainland contain, in the West, Rockies, Midwest and East, 4800, 4700, 4800 and 4700 direct receivers, respectively. These numbers maintain the number of ground stations as in the previous system. The number of Class 2 stations remains the same in Alaska and Hawaii but the 1000 stations on the mainland are grouped into 500 in the Rockies beam and 500 in the Eastern beam. The satellite now receives and transmits 125 voice channels at any given time in both the Rockies beam and the Eastern beam, but none in the West or the

Midwest. All of the beams still contain the 2 video channels. The cost comparison of this 6 beam system and the previous 3 beam system are given below (for beam coverage definitions see Figure 27 and 29):

	3 Beam System	6 Beam System	Cost Change
Total System Cost	265.699	228.406	-37.293
Space Segment Cost	113.379	117.000	3.621
Ground Segment Cost	150.503	111.406	-39.097

The small increase in space segment cost is expected since this satellite is constrained to use the same launch vehicle (Titan IIID/Burner II). The decrease of $39 million in the ground segment may seem surprising in that there are more transmitters and receivers on board the satellite which should decrease satellite transponder EIRPs. There are several factors which contribute to this cost decrease. First, since the narrowband channels are confined to two of the mainland beams, there is a savings in RF power radiated to the continental U.S. This savings proves to be considerable. In the three beam case, the satellite radiates a total of 224 watts of audio RF power, 218 of which is radiated to the mainland. In the six beam system a total of only 74.3 watts of audio RF power is radiated with a total of 55 watts divided between the Rockies beam and the Eastern beam. This means a savings of

150 watts of RF power over the 3 beam system and allows inclusion of additional video transponders in the satellite. This is evidenced in the fact that the video EIRP/channel in the six beam system is noticeably higher than in the three beam system. Another factor that leads to the ground segment cost reduction is the fact that on the mainland, in the three beam system, the worst case ground station has an elevation angle of 5^{o}, while the worst case in Hawaii is 36.6^{o}. The average elevation angle is 5.28^{o}. This demands that the direct stations must have a higher G/T and/or the satellite EIRP/channel must be high. In the six beam system, since all the mainland stations are not assumed to be at 5^{o} elevation, the average angle is 32^{o}. This allows less expensive ground stations and/or lower satellite EIRP/channel. In this particular system, the direct station G/T decreases and the satellite EIRP/channel increases. The Class 2 stations are also less expensive because of the fact that the satellite antenna gain for the Rockies beam and the Eastern beam is considerably higher because of smaller beam coverage than was the gain for the entire mainland beam in the three beam system. This allows lower transmitter powers in the Class 2 ground stations for establishing uplinks. The six beam interactive system was rerun using a larger launch vehicle (Titan IIIC/Burner II), to look into its impact over the system cost. The system cost (in million $) comparison is given below:

	Small LV (Titan IIID/ Burner II)	Large LV (Titan IIIC/ Burner II)	Cost Change
Total System Cost	226.405	243.730	15.324
Space Segment Cost	117.700	131.588	13.888
Ground Segment Cost	111.406	110.326	-1.08

The ground segment cost increase is apparently caused by the fact that the satellite for the larger launch vehicle is somewhat smaller than the size of that for the smaller launch vehicle, resulting in a comparable ground receiver G/T. The reason the satellite size does not increase with a larger launch vehicle (Titan IIIC/Burner II) is that the optimal satellite size for this system falls within the constraints of the smaller launch vehicle (Titan IIID/ Burner II). When the larger launch vehicle is chosen, the total space segment becomes more expensive because of the increased launch costs. The program tries to optimize the system cost by reducing the space segment cost through reduction in the satellite cost; this demands an increase in ground station performance. Thus the increased ground segment cost. Clearly, the smaller launch vehicle is optimal in this system.

The switch from the three beam system to the six beam system has advantages other than economic. With four separate master stations on the mainland there is a possibility of broadcasting eight different video channels simultaneously in the continental U.S. Also, since the four

beams correspond approximately to the time-zones, a program could be broadcast at the same local time throughout the U.S.

A disadvantage of the six beam system is that the interactive stations in the Rockies beam cannot communicate with the stations in Appalachia unless advanced transponders on board the satellite with interbeam channel switching are employed or if a low gain wide beam antenna to receive narrowband uplinks is used. If the system is intended as a master-slave configuration, this is not a major problem. However, if communication between the various interactive stations in different beams, this could be a serious problem resulting in increased system cost.

4.3 12 GHz BROADCAST SYSTEMS

The three beam, four video channel, non-interactive system described earlier was rerun with 12 GHz downlinks and 14 GHz uplinks in place of 6.2 GHz uplink for video, 2.5 GHz uplinks for narrowband return from remote small terminals and 2.6 GHz downlinks. This higher frequency case was run with Titan IIID/Burner II launch vehicle used in the lower frequency case but the results were unreasonable. The satellite weight would not reduce, for a reasonable ground segment environment, to the 2800 pound weight constraint imposed by Titan IIID/Burner II. The launch vehicle finally settled upon was a Titan IIIC$_7$ with a weight constraint of 4500 pounds.

The increased satellite weight is one of the penalties paid for using 12 and 14 GHz frequency bands for comparable capabilities at 2.5 and 6 GHz. The gain lies in the increased bandwidth availability. The increased weight is required by the transmitters which must produce greater RF power/channel as compared to that at 2.5 GHz because of considerably higher rain and atmospheric attenuation at 12 GHz. With the increase in RF power/channel, an increase in the raw power supply requirements is demanded and a corresponding satellite size increase occurs.

The cost comparisons between a three beam, four video channel per beam system at the 2.5 GHz and the 12 GHz band are given below (in million $):

	2.5 GHz System	12 GHz System	Cost Change
Total System Cost	216.376	299.661	83.285
Space Segment Cost	116.757	144.815	28.058
Ground Segment Cost	97.803	153.028	55.225

The space segment cost increase is due mainly to the increased RF power requirements resulting in increased satellite size and then a larger launch vehicle (Titan $IIIC_7$).

The 12 GHz system described above was rerun twice to determine the effect of the number of channels/beam on the system parameters and cost. The results for the system costs are shown in Figure 32. The EIRP/channel and the ground station G/T for the continental U.S. beams are shown

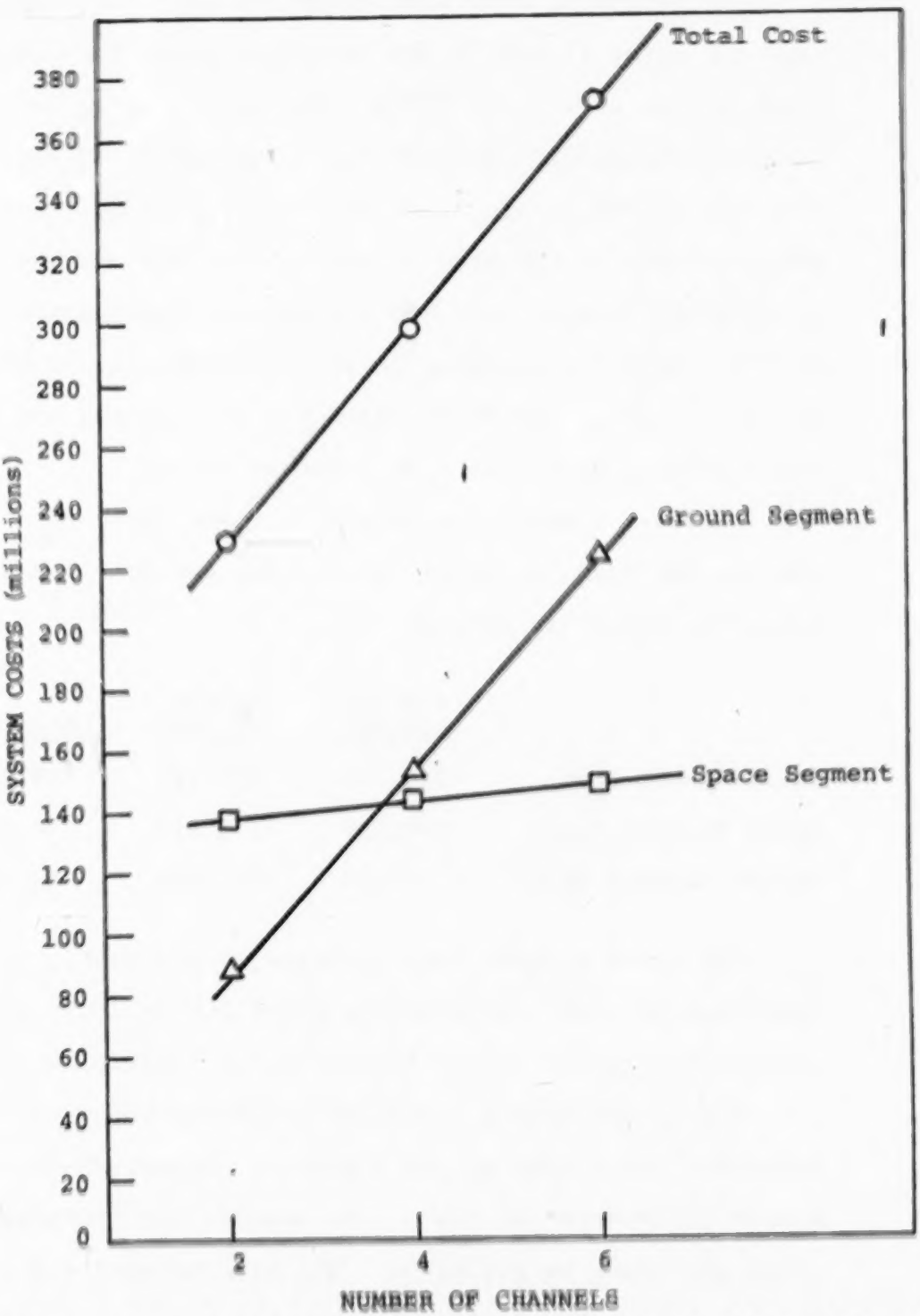

Figure 32: System Cost versus Number of Channels Broadcast

in Figure 33. The curves are very similar to Figures 21 and 22, for the 2.5 GHz systems. The reasoning behind the curves is the same in both cases. It is interesting to note, however, that the cost increase per channel in the 12 GHz system is roughly twice the cost increase per channel in the 2.5 GHz system. This ratio holds for both the ground segment and the space segment.

The three beam, six channel system used in the above comparison was rerun with the Hawaiian beam removed and then again with the Alaskan beam removed and the subsatellite point moved from 120° west to 100° west. The antenna coverage patterns for these systems are the same as in the 2.5 GHz case and are shown in Figures 26, 25 and 19. The effect of the number of beams on the system costing is shown in Figure 34. The corresponding 2.5 GHz curves are shown in Figure 27. The 12 GHz curves are very similar to those obtained for 2.5 GHz using the smaller launch vehicle (Titan IIID/Burner II) for all the three systems. In the 12 GHz system, for a given set of precipitation conditions, the optimal launch vehicle is the same for all three systems. The incremental cost per additional beam is roughly equal in the 12 GHz system to that in the 2.5 GHz system when using the smaller launch vehicle. However, when the optimal launch vehicle is used for the 2.5 GHz system, the cost increase, as a percentage of system cost, is roughly equal for the 2.5 GHz and 12 GHz systems.

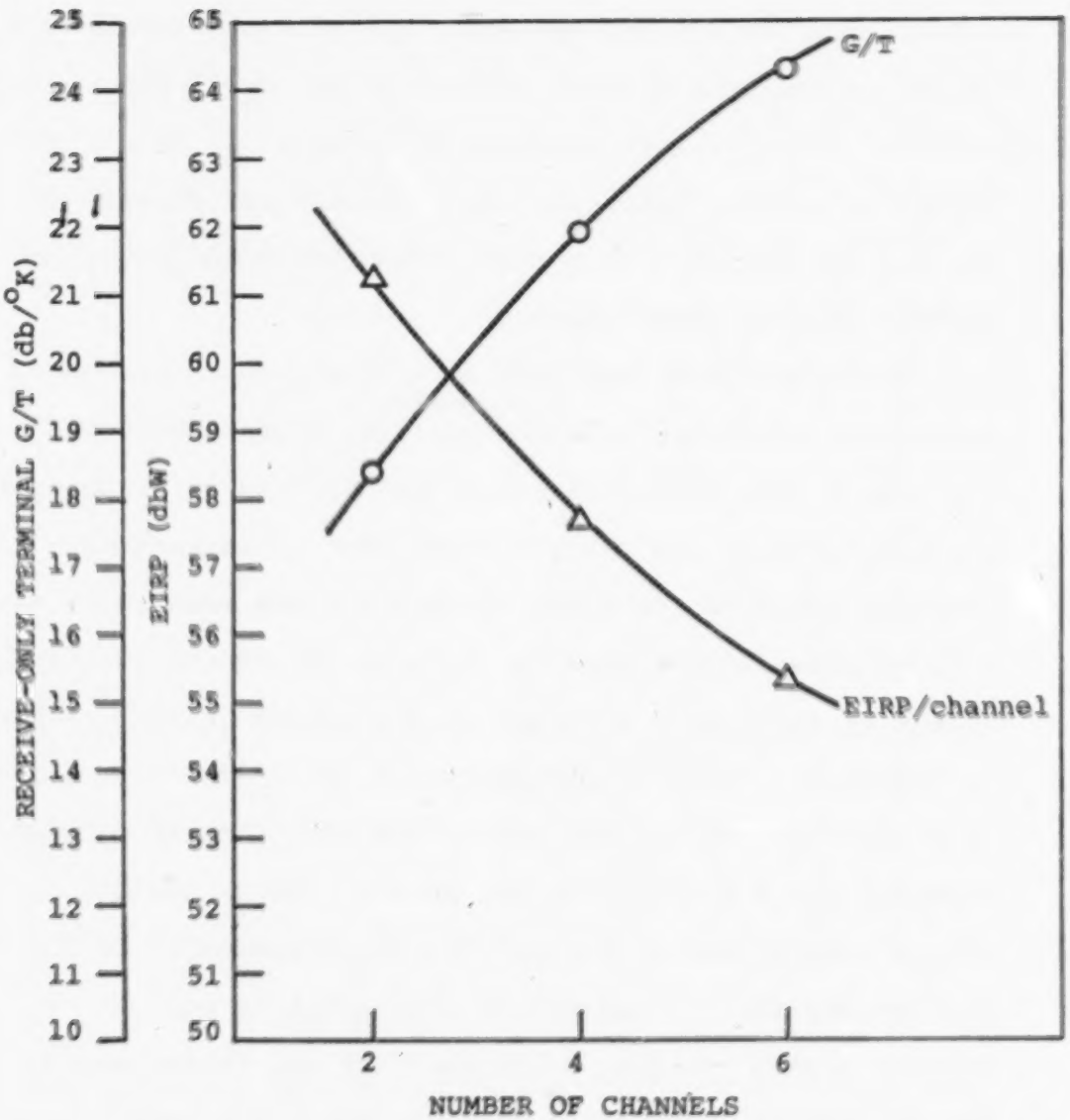

Figure 33: G/T, EIRP Versus Channels Broadcast

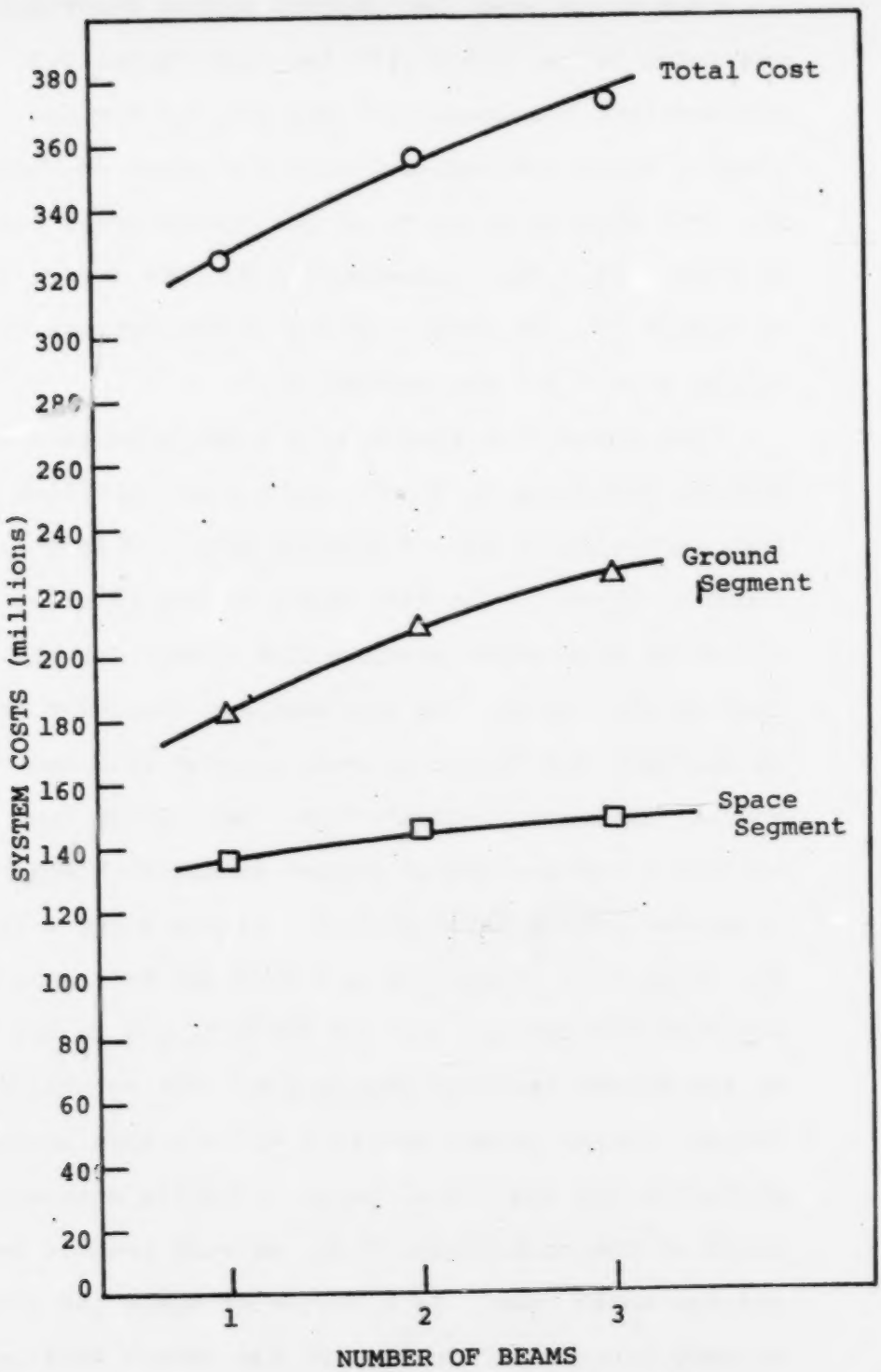

Figure 34: System Cost versus Coverage at 12 GHz

The three beam, two channel system described above was rerun twice, first with the continental U.S. coverage divided into two beams and then with it divided into four beams. These coverage patterns are shown in Figures 28 and 29. The results in terms of the system costs are shown in Figure 35. The corresponding 2.5 GHz curves are shown in Figure 30. In this case the 12 GHz systems do not behave as the 2.5 GHz systems do.

The transition from 3 to 4 beams effects a $33.5 million reduction in total system cost resulting primarily from reduction in ground segment cost. This could be understood in light of the fact that, in the three beam system, the worst case communication link design for the mainland beam is carried out for the smallest elevation angle (5 degrees) and the worst case regions from the viewpoint of heavier and more frequent rain. The system then tends towards a combination of higher satellite EIRP/channel and increased ground terminal G/T. In the 4 and 6 beam case, the worst case situations are confined to a single beam covering the eastern part of the U.S. and do not affect all of the ground terminal population. The satellite EIRP/channel and/or ground terminal G/T are then allowed to be different for individual beams, covering nonoverlapping parts of the continental U.S., as each beam is designed for its own worst case. In a situation where the satellite is already constrained in size by the launch vehicle, this

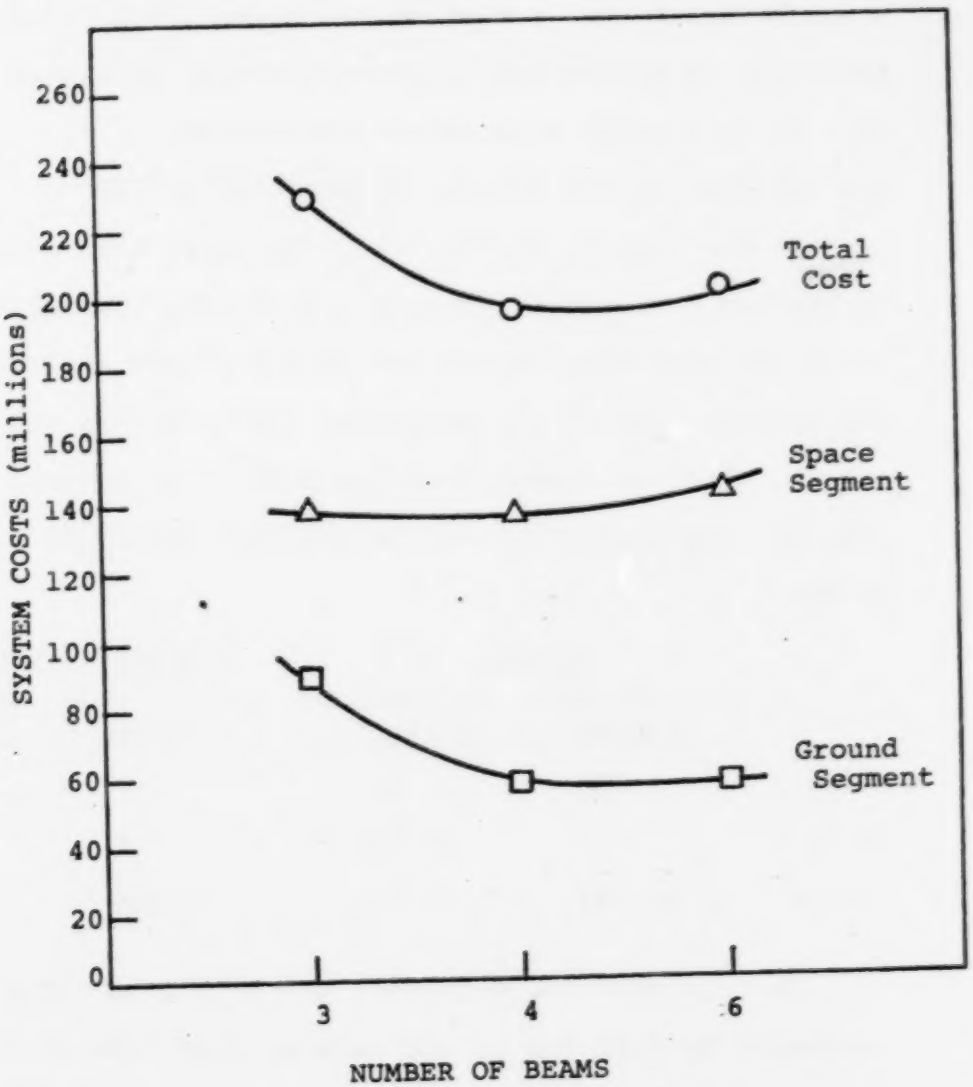

Figure 35: System Cost versus Regionalized Coverage at 12 GHz

results in a smaller G/T requirement for a large segment of the earth-terminal population and results in significant overall system cost reduction demonstrating a major advantage of having regionalized coverage if system operation in multimeter wave region is desired.

4.4 12 GHz LIMITED TWO-WAY INTERACTIVE SYSTEM

As was done in the 2.5 GHz, the three beam, 2 channel 12 GHz was modified to provide interactive capability in 12-14 GHz band for 1180 of the 20,650 ground stations in the system, 1000 on the mainland, 100 in Alaska and 80 in Hawaii. The cost comparison (in million $) between the receive only system and the interactive system is given below:

	Costs		Number of Stations	
	Receive Only System	Interactive System	Receive Only System	Interactive System
Class 1	0.892	1.264	3	3
Class 2	-	33.925	0	1,180
Direct	31.794	53.968	20,650	19,470

In this case the unit cost of the direct class stations increased by $260 due to the reduced satellite performance. The Class 1 station cost increases by an average of $124,000 per station with the greatest increase in the mainland Class 1 station. This is obviously due to the fact that the Class 1 stations have additional transmitters to handle and support talk-back or interaction. The cost of the

mainland Class 1 station is greater than those in the Alaskan and Hawaiian beam because of the worst-case location considerations. The Class 2 station cost averages $28,750 per station. As in the 2.5 GHz case, the difference in unit cost of Class 2 stations and the $2770 direct station is attributable to the audio transmitter and the smaller manufacturing learning that takes place.

Again assuming that all the Class 2 stations are clustered in the Rockies, Alaska and Appalachia, a six beam, 12 GHz narrowband interactive system was synthesized with the same requirements as for the 2.5 GHz system. The cost comparison of the 12 GHz 3 beam interactive and 6 beam interactive systems is given below:

	3 Beam System	6 Beam System	Cost Change
Total System Cost	381.955	252.925	-129.03
Space Segment Cost	140.500	135.762	-4.738
Ground Segment Cost	239.649	115.346	-124.303

The same launch vehicle (Titán $IIIC_7$) was used for both cases. In this case the space segment cost decreases by a small amount. Even though this change is relatively small, it may be surprising to many that the satellite should be less expensive when doubling the number of beams. It may be even more surprising in light of the fact that the ground segment cost decreases by $124.3 million. An inspection of the satellite parameter printout shows that the 16

transmitters in the six beam satellite weigh 389.1 pounds, an average of 24.3 pounds per transmitter. The nine transmitters in the three beam satellite weigh 332.2 pounds, an average of 37 pounds per transmitter. The prime power supply in the six beam satellite provides 4.8 kilowatts of power and weighs 696 pounds. The prime power supply in the three beam satellite provides 9.3 kilowatts and weighs 1345 pounds, almost double that of the six beam satellite. The total weight of the six beam satellite is only 3063 pounds compared to 4504 pounds of the three beam satellite. Since the launch vehicle chosen provides for a maximum satellite weight of 4500 pounds, it seems that this is not an optimal combination. The six beam system was rerun this time with a launch vehicle (Titan IIID/Burner II) with a 2800 pound weight limit. The cost comparisons are given below:

	3 Beam System	6 Beam System Titan $IIIC_7$ Launch	6 Beam System Titan IIID/ Burner II Launch
Total System Cost	381.955	252.925	226.763
Space Segment Cost	140.500	135.762	116.731
Ground Segment Cost	239.649	115.346	118.217

Obviously, the smaller launch vehicle is economically optimum, providing a $16 million reduction in total system cost. The cost of the ground segment increases slightly

from the system using the larger launch vehicle but this is expected due to the slight decrease in satellite size and, therfore, performance. The majority of the cost decrease in the space segment is due to the lower launch vehicle cost, a total of $19.5 million per launch assuming three launches. The smaller launch vehicle causes a decrease in the EIRP/channel of approximately .7 db in both audio and video channels in all beams. The direct station G/T increases by roughly the same .7 db which causes a cost increase of about $140 per direct station. The G/T of the Class 2 receiving system also increases by .7 db which contributes to an increase in cost of approximately $550 per station. This cost increase is also caused by increased Class 2 terminal transmitter performance.

4.5 EFFECT OF RAIN RATE

The single beam, 2.5 GHz system providing 4 video channels to 20,000 ground receiving stations on the continental U.S. was resynthesized three times with the worst rain rate, which has been assumed to be 3.5 mm/hr for all previous cases, changing from 5 mm/hr to 10 mm/hr and 15 mm/hr. These three cases were run again at 12 GHz. The effect on the system costing is shown in Figure 36 and the impact of heavier rain on 12 GHz systems is obvious.

4.6 COMPARISON OF STAMP TO CSC PROGRAM

The Computer Science Corporation used its broadcast satellite system synthesis program (8) to synthesize a

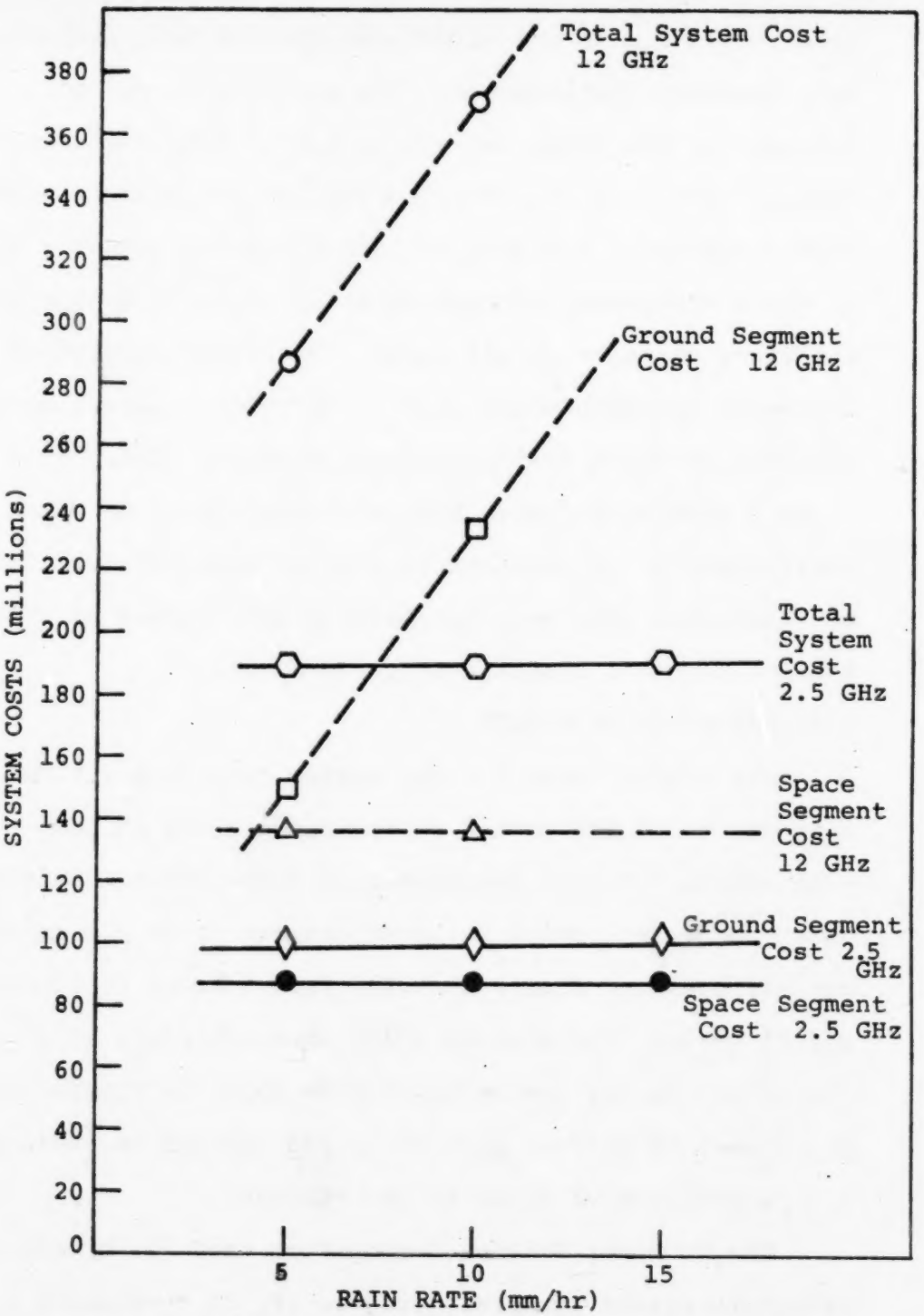

Figure 36: Impact of Rain Protection over System Cost

satellite broadcasting system for educational television in the U.S. The system was composed of 15,000 receiving stations, 5000 in each of 3 beams (2^{o} x 2^{o} beams covering Alaska, Rockies and the Appalachian region). Six television channels were broadcast from the satellite in the 12 GHz band in each beam. The coverage patterns are shown in Figure 37. The primary optimal system characteristics computed by CSC are summarized below:

EIRP/channel = 51 db

Satellite weight = 2047 lbs.

RF power/channel = 124 watts

G/T (beam 1, Alaska) = 21.4 db/^{o}K

(beam 2, southwest) = 20.0 db/^{o}K

(beam 3, mid southern) = 20.8 db/^{o}K

System cost = $208 million

A very similar system was synthesized using the modified STAMP for comparison and validation. Several facts must be noted first concerning the two computer programs. First, the CSC program does not provide in its costing routine for annual opearting costs. Therefore, its total system cost is actually equivalent to the initial investment portion of the GD/C program. Second, the CSC program, in its optimization routine, assumes that the characteristics of each beam are identical at the satellite and the ground stations differ depending on the losses and noises incurred in each beam. The GD/C program, on the other hand, assumes the Class 2 and 3 ground receiving stations are mass produced

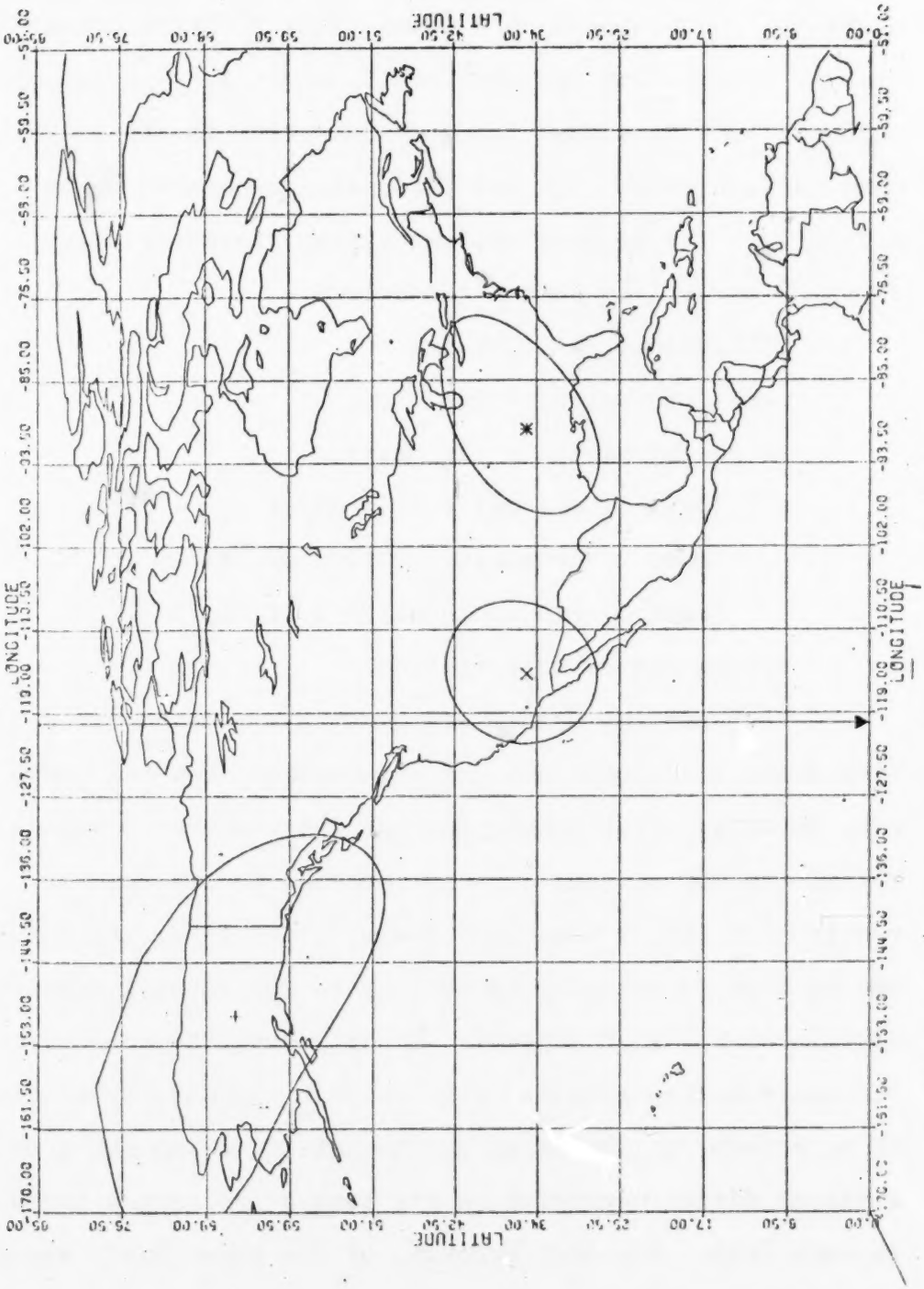

Figure 37: Three Beam Coverage To Alaska and Parts of CONUS

and are, therefore, identical. The transmitter and receiver characteristics of each beam differ at the satellite to account for the losses and noises in each beam. Third, the CSC program chooses a launch vehicle automatically based on the size of the satellite, while the GD/C program requires that a launch vehicle be chosen, a priori and the program tries to fit the satellite to the launch vehicle. In this particular STAMP run Titan IIID/Burner II was chosen as the launch vehicle. The CSC program computed the satellite weight to be 2047 pounds and the Titan IIID/Burner II has a weight of 2800 pounds.

The system characteristics computed by the modified STAMP for same inputs as those used in CSC system definition, are summarized below:

EIPR/channel, (Beam 1, Alaska) = 48.7 dbW
(Beam 2, Southwest) = 51.2 dbW
(Beam 3, Middle Southern) = 52.1 dbW

Satellite Weight = 2800 pounds

RF Power/Channel, (Beam 1) = 175 watts
(Beam 2) = 32 watts
(Beam 3) = 38 watts

G/T, (Beam 1) = 19.57 db/^{o}K
(Beam 2) = 20.13 db/^{o}K
(Beam 3) = 20.06 db/^{o}K

System Costs:

Total capital investment	=	$209.160 million
Total annual operating costs	=	$ 70.289 million
		$279.449 million

Looking first at the EIRP/channel, it is clear that, in the GD/C program, the beam 2 and beam 3 values are very similar to those obtained from the CSC program. However, as is expected, the EIRP/channel in the Alaskan beam is considerably higher due to the increased path length and the fact that all the ground terminals in the system are identical. The poorer conditions in Alaska are accounted for in the CSC program by the fact that the ground receiving stations in Alaska are designed to provide a higher G/T than the stations in beams 1 and 2.

At first glance it appears that the costing of the two programs is amazingly close, the CSC program yielding $208 million and the GD/C program giving $209 million for its initial investment figure. However, on further examination it can be seen that the fact the two figures are so close is coincidental to some degree since the CSC program shows a $119 million space segment and an $89 million ground segment compared to the STAMP which computes a $145.2 million space segment and $61.6 million ground segment. The STAMP also includes, in the costing of the total system, the costs of the video origination stations and the costs of the telemetry and command.

In brief, the two programs came reasonably close on the EIRP/channel and the ground station G/T, the two most important system parameters, but the subsystem costing routines of the two programs are inconsistent.

4.7 EFFECT OF INTEREST AND INFLATION RATES

The GD/C program was rerun to synthesize the system described in the previous section except that this time the time value of money was taken into account by inputting an inflation rate and an interest rate of 3.5% and 10%, respectively. The cost comparisons (in million $) are given below:

	No Interest or Inflation	Interest and Inflation	Present Value Change
Total System Value	279.448	226.865	-52.583
Space Segment Value	145.158	117.729	-27.429
Ground Segment Value	131.745	107.321	-24.424

It is interesting, in this case, to note that in both systems, the satellites and launch vehicles are virtually identical and yet the present value of the space segment is over $27 million different than the dollar value of three satellite-launch vehicle combinations. Also, the ground stations are virtually the same in both cases yet the ground segment cost decreases by $24 million when the interest and inflation are accounted for. The initial costing for the ground segment is very close, differing

by only $0.236 million while the average annual costs differ by only $0.022 million. The present value of the total annual operating cost of the system, for the case with interest and inflation assumed to be zero, is merely the average annual cost multiplied by the system lifetime of 15 years. This gives a total of $70.3 million. However, when an interest rate or 10% and an inflation rate of 3.5% enter the picture the present value of the total annual cost is only 9.54 times the average annual cost giving a value of $44.9 million.

The program was rerun with the previous inputs but with an interest rate of 15%. The system cost comparisons for two different interest rates are shown below:

	Interest = 10%	Interest = 15%	Present Value Change
Total System Value	226.865	203.766	-23.099
Space Segment Value	117.729	104.080	-13.649
Ground Segment Value	107.321	98.230	-9.091

In these systems the ground and space segments are, again, very similar* but the present value of the total annual expenses is reduced from $44.9 million to $34.2 million. The system synthesized with a 10% interest rate

*The unchanging nature of the satellite and ground terminal parameters is attributable to the launch vehicle constraints.

exhibited a slightly higher EIRP/channel at the satellite and a correspondingly lower ground station G/T than in the system synthesized at 15% interest. There is a reason for this effect; the present value of the total annual ground segment expenses is computed in the following manner:

$$PVAOC = AOC \cdot (\#\ \text{of stations}) \cdot PVFG$$

where, PVAOC = present value of annual operating costs for the ground segment

AOC = annual operating costs for the ground segment

PVFG = present value factor for ground segment =

$$\sum_{k=1}^{15} \left(\frac{1 + inf}{1 + int}\right)^k$$

When the interest or discount rate is assumed to be 10%, $PVFG_{10} = 9.5368$. With a 15% interest rate $PVFG_{15} = 7.1469$.

The cost of the space segment is computed as follows:

$$PVSS = UCSS + UCSS \left(\frac{1 + inf}{1 + int}\right)^5 + UCSS \left(\frac{1 + inf}{1 + int}\right)^{10}$$

where, PVSS = present value of the space segment

UCSS = the unit cost of one satellite-launch vehicle combination.

The present value factor for the space segment, PVFS, is given as:

$$PVFS = 1 + \left(\frac{1 + inf}{1 + int}\right)^5 + \left(\frac{1 + inf}{1 + int}\right)^{10}$$

With a 10% interest rate $PVFS_{10} = 2.2813$. At 15% interest $PVFS_{15} = 1.9392$.

Now, for the ground segment, $PVFG_{10} = 1.33\ PVFG_{15}$ while for the space segment $PVFS_{10} = 1.17\ PVFS_{15}$. This says that as the interest or discount rate decreases, the impact of the ground segment cost on the total system cost will grow faster than the space segment cost impact. In other words, at lower interest rates, a unit cost change in the annual operating cost of the ground segment will have a larger effect on the total system value than will a unit cost change in the space segment cost. Therefore, at the lower interest rate of 10%, the program, as it reduces the total system value, is actually reducing the ground segment cost more than it does with an interest rate of 15%.

The system was synthesized again with the interest and inflation rate set at 10% and 3.5%, respectively. However, a ground station population growth was introduced. The growth starts at zero facilities and grows to the maximum in 3 years time. The growth rate parameter (see Section 3.9), β, is set at 0.3. This is saying that all the ground stations are not available at system startup and the initial costs for these stations will not occur until some future date. These costs will be discounted to the present value and the present value of the initial costs will be smaller than the case where all the ground terminals in the system are assumed to be deployed at the time of satellite launch. Also, the present value of the annual expenses should be lower with the growth curve since the annual costs for the

delayed stations are not incurred until after the stations are built. The cost comparisons (in million $) between the case with the growth curve and the case without it are shown below:

	System Without Growth	System With Growth (β=0.3, T=0)	Present Value Change
Total System Value	226.865	220.244	-6.621
Space Segment Value	117.729	117.019	-0.710
Ground Segment Value Initial Costs	63.632	60.452	-3.180
Total Annual Costs	43.626	40.957	-2.669

As can be seen, this present value of the ground segment decreases as expected. The space segment is relatively constant in both systems. The small change that is present could be due to the fact that the program sees a lower value for the ground segment in the system with the growth curve and therefore will try to increase the ground segment cost and hence decrease the space segment cost slightly.

The same program was run twice again, with the growth rate parameter (β) equal to 1.5 and 6. The effect on the present value of system cost is shown in Figure 38. In all cases the value of the space segment remains constant while the present value of the ground segment decreases with increasing β. As β increases, the rate of growth decreases. Then, for the larger values of β, there will be a greater percentage of the ground station costs occurring late.

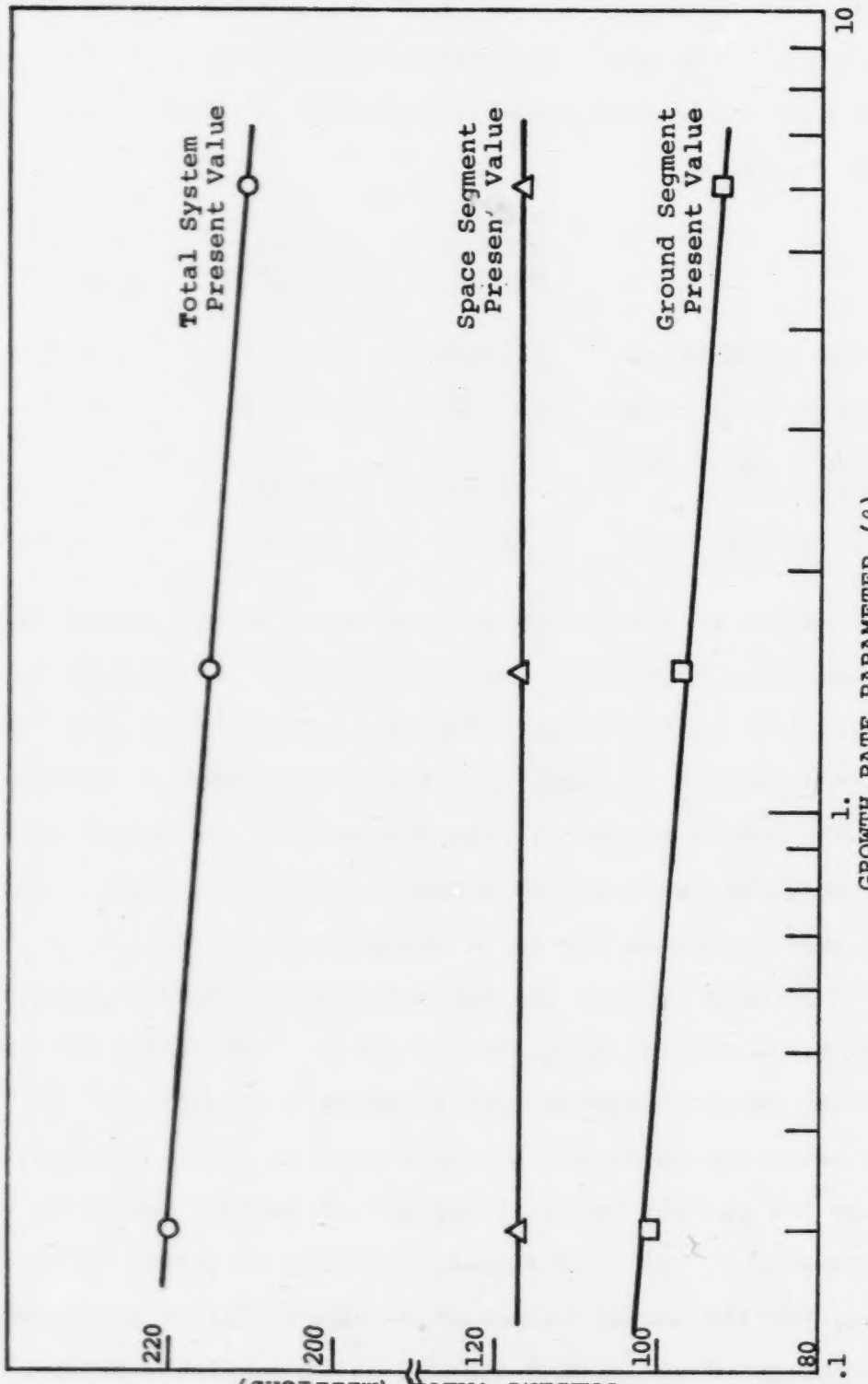

Figure 38: Present Value of a System As a Function of Growth Rate Parameter (β)

These "late" costs are discounted to the present value and contribute to a lower total system present value. Thus, the larger is the growth rate parameter (β), the lower is the total system present value.

The case with $\beta = 6$, with the interest and inflation equal to 10% and 3.5%, respectively, was run once more, this time with satellite spare in orbit to increase the reliability and the service continuity of the system. Since there are three generations of satellites in the 15 year system lifetime, assuming a five year satellite lifetime, three orbit spares are included in the total system value. One of the anomalies of the optimization program presents itself in this case. On the one hand, the value of the space segment will be roughly twice the previous value and the program will try to reduce the space segment to decrease the total system present value. On the other hand, an increase in the ground segment performance necessary to lower the space segment cost also causes a considerable increase in ground segment value. These two factors contribute to a very slow convergence process. This particular case was run for a total of 70 iterations and convergence had not been achieved; however, it could be seen from the individual iteration printouts that the size of the satellite and, therefore, the total space segment value was decreasing. It was decreasing at so slow a rate that it did not seem economically advantageous to run the program until convergence was reached. A similar

problem was encountered when a ground satellite spare was added to the above system. Experience suggests that this very slow convergence is the exception rather than the rule.

5. SUMMARY AND CONCLUSIONS

The subject of computer-aided fixed/broadcast communications satellite system synthesis and optimization has been of interest to a number of individuals and organizations for several years. The amount of numerical computations involved in defining the lowest-cost system or configuration for a given set of user and technical requirements and constraints is considerably large and rather repetitive and for this reason it is advantageous to use the computer for synthesizing an optimal system.

In the recent years, the National Aeronautics and Space Administration (NASA) has sponsored the development of several computer programs for either fixed or broadcast satellite system synthesis. One of these programs, (9) developed at the Stanford University, is focussed on satellite systems for teleconferencing. Another, developed by the Computer Sciences Corporation,(8) is for evaluation and synthesis of broadcast satellite systems. A third program, developed by the Convair Division of the General Dynamics Corporation (7) and named Satellite Telecommunication Analysis and Modeling Program (STAMP), could be used for the synthesis of either a fixed or broadcast system or a system that combines both services.

The Stanford University program (9) is applicable primarily to teleconferencing situations and is rather limited in its capabilities. It only defines an optimized

earth segment for a given set of user requirements, terminal population, and a space segment defined in terms of the annual cost of one watt of satellite RF output power. Its algorithm for determining the least-cost system is rather inefficient in that its approach is that of "try all possible combinations of independent variables and pick the combination that yields the least cost system."

The computer program developed for NASA by the Computer Sciences Corporation (8) is applicable only to broadcast systems. Although up-to-date as far as the definition of the technical environment is concerned, it lacks a methodology for computing and comparing total system costs of alternate systems.

The Satellite Telecommunication Analysis and Modeling Program (STAMP), developed for NASA by GD/C in 1970-71, is rather complete and flexible though lacking an up-to-date technological environment and limited to the definition of systems employing analog modulation and Frequency Division Multiple Access (FDMA). STAMP can handle up to six beams, three kinds of earth-terminals, and fixed as well as broadcast systems. The optimization technique employed in STAMP is a steepest-descent interactive procedure which is considerably more efficient than the optimization procedures used in the other two programs. STAMP, in contrast to the Stanford University program, utilizes a total system approach and determines the minimum cost system configuration subject to fixed user requirements and imposed constraints.

The user requirement investigations conducted at Washington University suggest that educational satellite service requirements represent a mixture of point-to-point, teleconferencing and broadcast services. While many of the possible services require a wideband receive and narrow-band voice/data transmit ability, there are many that require wideband receive-only or symmetrical video/voice/data transmit-receive capabilities. Thus, a tool for synthesis of minimum-cost educational satellite systems is required to have an ability to consider different types of earth-terminals, broadcast as well as fixed satellite services in one system, and a large number of beams in view of the decentralized nature of U.S. education. In view of the availability of many of the above features in GD/C STAMP program and its modular construction which permits alterations with relative ease, STAMP was chosen to be the base for a number of modifications to provide a more powerful, up-to-date and an appropriate tool for handling the system costing and evaluation requirements of the Washington University interdisciplinary research Program on Application of Communication Satellites to Educational Development.

The modifications made to STAMP implemented on Washington University's IBM 360/65 computer system include: extension of the six beam capability to eight; addition of an option for generating multiple beams from a single

reflector with an array of multiple point-feeds; an improved system costing to reflect the time value of money, growth in earth-terminal population, and to account for various measures of system reliability; inclusion of a model for scintillation at microwave frequencies in the communication link loss model for near-equatorial coverages; and, an updated technological environment. The modifications are described in Chapter 3 along with the definition and listing of all new input variables added to the modified STAMP.

A preliminary sensitivity analysis has been carried out with the aid of the modified STAMP to investigate the sensitivity of system characteristics and cost to variations in user and technical requirements and imposed constraints. The modified STAMP has also been used to define a 3-beam 12 GHz broadcast system for a set of user and technical inputs used in the Computer Sciences Corporation study (9) for the definition of a baseline system for the purposes of comparing the two programs. The technical characteristics of the system defined by modified STAMP are strikingly similar to those defined by CSC. The results of this work are described in detail in Chapter 4 though some conclusions drawn from the preliminary analysis are presented here.

For most systems there is an optimal launch vehicle. Choosing a smaller vehicle increases the ground segment cost more than necessary by constraining the satellite size, and therefore, the performance of the satellite. On

the other hand, choosing a larger vehicle also increases the ground segment costs more than necessary. This is because the program tends to reduce the space segment cost to a greater degree than is necessary because of the higher launch cost. Therefore, the choice of an appropriate launch vehicle is quite important in the synthesis of the least cost system.

When considering an educational television broadcast type of system, the transition from a single beam covering the continental U.S. to a 2 beam system covering the mainland and Alaska causes an increase of 8% in the total system cost. However, by using a larger launch vehicle, the cost of the ground receiving stations can be reduced by close to 10%. The shift to a three beam system covering Hawaii causes total system cost increase of 13% over the single beam system.

The location of the satellite in a three beam broadcast system covering Alaska, Hawaii, and continental U.S. simultaneously can range from 120° west to 100° west with no noticeable change in total system cost for a common set of service requirements in each beam. Apparently, the degradation of conditions due to decreased elevation angles, when the satellite is at 100° west, in Alaska and Hawaii is balanced by the improved conditions on the mainland.

In using the GD/C program to compare an interactive system with an otherwise identical receive-only system,

the cost increase is due not only to the increased number of transmitters necessary but also to the fact that the number of identical receiver systems for mass production is reduced. This will reduce the cost reduction due to mass production.

A considerable savings can be realized if separate beams are used to interconnect wideband receive and narrowband transmit type earth terminals clustered into small regions. In this case the mainland beam can be split into several narrower beams with the narrowband channels transmitted only to those areas that use it.

The operating frequencies play a part in the sensitivity of system cost to various parameters. At higher frequencies, particularly frequencies above 10 GHz, the attenuation due to the troposphere increases and makes higher EIRP/channel values necessary and, consequently, heavier and larger satellites for a given set of user requirements.

When increasing the number of channels per beam, however, the incremental cost per channel, expressed as a percentage of the total system cost is roughly equal at 12 GHz to that at 2.5 GHz. On the other hand, in changing from a receive only system to an interactive system, the total system cost increased by 66% at 12-14 GHz while only increasing 50% at 2.5 GHz. The change from the 3 beam interactive system to the 6 beam interactive system caused a 34% total cost decrease at 12 GHz, while at 2.5 GHz it effected only a 14.6% decrease. At higher frequencies,

it generally shows a dependence on the same variables as at lower frequencies but it shows the dependence to a greater degree.

It has been demonstrated that the comparison of any two systems must take into consideration the effects of interest and inflation. Two systems that have the same total costs may actually be several million dollars different when looked at in terms of the time-value of money.

The interest rate adds another aspect to be considered in the determination of the system value. At lower interest rates, the system cost reduction has a greater impact on the ground segment while at higher interest rates the effect is greater on the space segment.

The interest and inflation rates are also important when ground terminal population growth curves are defined in the system. The costs of stations built after system startup are discounted to the present value resulting in a lower system value. The slower growth rate implies smaller total system present value. However, if the ground station population growth rate is known a decision should be made as to when the satellite should be launched to provide optimal use of the satellite lifetime.

In conclusion, it could be stated the the modified STAMP computer program described in this report is a flexible yet powerful tool for educational fixed/broadcast

satellite system synthesis and evaluation to be used in the early system planning stages. The modified STAMP can be used for evaluating the tradeoffs between system performance and cost, to perform sensitivity analyses to identify critical user and technical requirements, and to synthesize the least-cost system for a fixed set of user requirements, technological environment and imposed constraints. Its limitation lies in the fact that in its current form it can only synthesize fixed/broadcast satellite systems using Frequency Modulation (FM) and Frequency-Division Multiple Access (FDMA). An effort, in the form of another M.S.E.E. thesis,(19) is underway to develop a capability for computer-aided synthesis of least-cost fixed satellite systems using digital transmission techniques for voice/data and FM for video information with narrowband communication in either Frequency- or Time-Division Multiple Access (TDMA) mode. This work, scheduled for completion in the near future, will complete the inventory of the requisite set of tools for synthesis and evaluation of alternative educational fixed/broadcast satellite systems being carried out at the Washington University.

6. ACKNOWLEDGMENT

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7. APPENDICES

7.1 COMPUTER AIDS FOR SYSTEM SYNTHESIS

Please see:

Reference 16: Stagl, Thomas W. and Singh, Jai P., "A Computer Program for Mapping Satellite-Borne Narrow-Beam Antenna Footprints on Earth," Memorandum No. 72/3, Center for Development Technology, Washington University, St. Louis, Missouri, March 1972.

Reference 17: Stagl, Thomas W. and Singh, Jai P., "Computer Programs for Plotting Spot-Beam Coverages from an Earth-Synchronous Satellite and Earth-Station Antenna Elevation Angle Contours," Memorandum No. 72/4, Center for Development Technology, Washington University, St. Louis, Missouri, October 1972.

7.2 MODIFIED STAMP LISTING

The modified STAMP listing is available by request.

8. BIBLIOGRAPHY

1. Morgan, R. P., Singh, J. P., Anderson, B. D., and Greenberg, E., "Satellites for U.S. Education: Needs, Opportunities and Systems," in Communication Satellites: Systems and Advanced Concepts, (Editor: P. L. Bargellini), MIT Press, Cambridge, Massachusetts, (in press).

2. Lutz, S. G., "Economic Factors Influencing the Breakeven Relations Between Satellites and Terrestrial Point-To-Point Communications," Telecommunications Journal, Vol. 36, No. 7, July 1969, pp. 317-318.

3. McClure, R. B., "The Effect of Earth-Station and Satellite Parameters of SPADE System," IEE Conference on Earth-Station Technology, The Institution of Electrical Engineers, London, October 1970, pp. 17-23.

4. Charkraborty, D., "Intelsat IV Satellite System Channel Capabilities versus Earth-Station Performance," IEEE Transactions on Communication Technology, Vol. COM-19, No. 3, June 1971, pp. 353-362.

5. Kiesling, J. D., et al., "A Technique for Modeling Communications Satellites," COMSAT Technical Review, Vol. 2, No. 1 (Spring 1972), pp. 73-103.

6. Hasselbacher, R. W., "Television Broadcast Satellite (TVBS) Study," Report No. NASA CR-72578, Space Division, General Electric, Valley Forge, Pennsylvania, August 1969.

7. Bergin, Patrick, et al., "Information Transfer Satellite Concept Study--Final Report," in four volumes, NASA Contractor Report No. CR-114312, Convair Aerospace Division of the General Dynamics Corporation, San Diego, California, May 1971.

8. Knouse, George, et al., "A Computer Program for Evaluating and Synthesizing Broadcasting Satellite Systems," Final Report No. 4169-011, NASA Contract No. NASN-2354, Computer Sciences Corporation, Falls Church, Virginia, April 1973.

9. Potter, James, "Minimum Cost Satellite Teleconferencing Networks," in Teleconferencing: Cost Optimization of Satellite and Ground Systems for Continuing Professional Education and Medical Services, A Report Prepared for the National Aeronautics and Space Administration by the Institute for Public Policy Analysis, Stanford University, Stanford, California, May 1972.

10. Taur, R. R., "Ionospheric Scintillation at 4 and 6 GHz," COMSAT Technical Review, Communication Satellite Corporation, COMSAT Labs, Clarksburg, Maryland, Spring Issue, 1973.

11. Andrus, A. M. Greg, "A Survey of High Power Communication Satellite System Technology," presented at IEEE International Conference on Communications, Philadelphia, Pennsylvania, June 19-21, 1972.

12. Craft, H. D., Jr. and Westerlund, L. H., "Scintillations at 4 and 6 GHz caused by the Ionosphere," presented at AIAA 10th Aerospace Science Meeting, San Diego, California, January 17-19, 1972.

13. Bellamy, Jack L., "Multibeam Antenna Study," Phase II--Final Report (Draft), NASA Contract No. NAS5-21711, Lockheed Missiles and Space Company, Sunnyvale, California, September 1972.

14. Zolnay, S. L., "Earth Coverage ('Footprint') of a Satellite-Borne Antenna," Technical Note 1971-7, Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts, February 5, 1971.

15. Saad, Theodore S., "Antennas," in Microwave Engineers Handbook (Vol. 2), Dedman, Massachusetts: Artech House, Inc., p. 24.

16. Stagl, Thomas W. and Singh, Jai P., "A Computer Program for Mapping Satellite-Borne Narrow-Beam Antenna Footprints on Earth," Memorandum No. 72/3, Center for Development Technology, Washington University, St. Louis, Missouri, March 1972.

17. Stagl, Thomas W. and Singh, Jai P., "Computer Programs for Plotting Spot-Beam Coverages from an Earth-Synchronous Satellite and Earth-Station Antenna Elevation Angle Contours," Memorandum No. 72/4, Center for Development Technology, Washington University, St. Louis, Missouri, October 1972.

18. "Technical and Cost Factors That Affect Television Reception from a Synchronous Satellite," Report TR-PL-9037, NASA Contract NASW-1305, Jansky and Bailey Systems Engineering Department, Atlantic Research, Washington, D.C., June 1966.

19. McCuller, J. B. and Singh, J. P., "A Computer Program for Small-Terminal Fixed/Broadcast Satellite System Parameter Optimization," Center for Development Technology, Washington University, St. Louis, Missouri (forthcoming).